# REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188



**1. AGENCY USE ONLY** *(Leave blank)*

**2. REPORT DATE**
1995

**3. REPORT TYPE AND DATES COVERED**

**4. TITLE AND SUBTITLE**
A Methodology for Evaluating Systems Engineering And An Approach for Exploring it effectiveness - Demonstrated With Case Studies of Recent Aircraft Development Effort.

**5. FUNDING NUMBERS**

**6. AUTHOR(S)**
Jay Alan Moody

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
AFIT Students Attending:
The University of Arizona

**8. PERFORMING ORGANIZATION REPORT NUMBER**
AFIT/CI/CIA
95-016

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
DEPARTNEMT OF THE AIR FORCE
AFIT/CI
2950 P STREET, BDLG 125
WRIGHT-PATTERSON AFB OH 45433-7765

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**



**11. SUPPLEMENTARY NOTES**

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for Public Release IAW AFR 190-1
Distribution Unlimited
BRIAN D. GAUTHIER, MSgt, USAF
Chief Administration

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*

"Original contains color plates: All DTIC reproductions will be in black and white"

**14. SUBJECT TERMS**

**15. NUMBER OF PAGES**
288 + 12

**16. PRICE CODE**

**17. SECURITY CLASSIFICATION OF REPORT**

**18. SECURITY CLASSIFICATION OF THIS PAGE**

**19. SECURITY CLASSIFICATION OF ABSTRACT**

**20. LIMITATION OF ABSTRACT**

# A METHODOLOGY FOR EVALUATING SYSTEMS ENGINEERING AND AN APPROACH FOR EXPLORING ITS EFFECTIVENESS - DEMONSTRATED WITH CASE STUDIES OF RECENT AIRCRAFT DEVELOPMENT EFFORTS

by

Jay Alan Moody

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A Thesis Submitted to the Faculty of the

DEPARTMENT OF SYSTEMS AND INDUSTRIAL ENGINEERING

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE
WITH A MAJOR IN SYSTEMS ENGINEERING

In the Graduate College

THE UNIVERSITY OF ARIZONA

1995

## STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree of The University of Arizona.

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SIGNED: Jay Alan Moody

## APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

A. Terry Bahill — May 10, 1995

A. Terry Bahill
Professor of Systems and
Industrial Engineering

Date

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## ACKNOWLEDGMENTS

My thanks go to the United States Air Force for sponsoring my master's degree program.

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# ABSTRACT

This thesis proposes a methodology for measuring the extent to which basic systems engineering principles and practices are followed during a system development effort, as well as for measuring other characteristics of the system development process, in attempts to relate the success of the development effort to the degree of systems engineering. The approach enables the evaluation and rating of case studies, regardless of system type or size, based on figures of merit and rating criteria developed for each of five characteristics of the system development process as modeled. The scoring methodology is demonstrated using six case studies of recent commercial and military aircraft development programs, including the Boeing 777, Lockheed F-117, Northrop B-2, McDonnell Douglas C-17, Learjet Model 60, and McDonnell Douglas MD-11. The primary purpose for conducting this effort is to provide a tool to enhance systems engineering understanding and education.

# INTRODUCTION

The attempt to understand the effectiveness of performing systems engineering practices during the development of complex systems is hindered by the lack of a common definition of systems engineering and a methodology to measure its degree of application. What has also been lacking is a top-level model that relates various characteristics of the system design process to the results of the development, namely, technical performance, cost performance, and schedule performance. These outcomes, comprising the *performance* measure, define the extent of overall success of the system development effort.

This thesis proposes a methodology for rating case studies of past system development efforts based on criteria developed for each characteristic of the system development process. Furthermore, it is proposed that the scores may be used to perform a comparison between different case studies in order to explore the empirical relationships between the different characterstics of the system development process. These characteristics, in addition to the *performance*, include *systems engineering fundamentals*, *development environment*, *design difficulty*, and *resources* to accomplish system development. This effort is intended primarily to provide a tool to enhance systems engineering understanding and education.

# CHAPTER 1

# EVALUATING SYSTEMS ENGINEERING

"Systems engineering" is a relatively common term used in the engineering world. Despite the recognition, there is no exact, universal definition of what systems engineering is and what it denotes. However, there appears to be a common belief that systems engineering, whatever its specific definition, is an important if not crucial element in the successful development of complex entities composed of hardware, software, and people. Over the past 20 years, there has been an emerging consensus as to the definition of systems engineering and the importance of following its principles as part of the system design process. However, what is the basis of the belief in the importance of systems engineering? Most case studies describing a system development never mention the word systems engineering or outline the application of whatever it constitutes. To be able to determine whether or not systems engineering is actually an important factor in the development of systems, there should be a standard, concise way to measure and represent the degree to which the discipline is followed during development. Since systems engineering involves a wide range of concerns, and it means different things to different people, evaluating it in a manner that everyone can agree with becomes a tremendous challenge. The first step towards being able to measure and evaluate impact is

to understand what systems engineering fundamentally is.

Definitions now abound. Five of them are presented below:

According to Dr. A. Wayne Wymore in *Model Based Systems Engineering*, "Systems engineering is the intellectual, academic, and professional discipline the principal concern of which is the responsibility to ensure that all requirements for a system are satisfied throughout the life cycle of the system."

According to the draft version of MIL-STD-499B, "Systems engineering is the management and technical process that controls all engineering activities throughout the life cycle in order to achieve an optimum balance of all system elements to ensure satisfaction of system requirements while providing the highest degree of mission success. It has two main activities: (a) interpreting the customer's needs and translating them into a set of requirements that can be met by individual design and specialty disciplines and (b) validating that the system satisfies the customer's needs through analysis, simulation, and testing."

According to the Defense Systems Management College *Systems Engineering Management Guide*, "Systems engineering is the management function which controls the total system

development effort for the purpose of achieving an optimum balance of system elements. It is a process which transforms an operational need into a description of system parameters and integrates those parameters to optimize the overall system effectiveness."

According to *Successful Systems Engineering For Engineers and Managers* by Norman B. Reilly, "Systems engineering is the systematic application of proven standards, procedures, and tools to the technical organization, control, and establishment of system requirements, system design, system management, system fabrication, system integration, system testing, and system logistics support."

According to the draft *IEEE P1220 Standard for Systems Engineering*, systems engineering is an interdisciplinary collaborative approach to derive, evolve, and verify a life-cycle balanced solution that meets customer and public acceptability.

The definitions say similar things. For the most part, differences in definition reside in the terminology and details of what specific activities it constitutes, the scope to which it is applied, and when in the life cycle it is appropriate. Since the definitions above are broad, they do not provide a concrete understanding to lay persons of what systems engineering

involves. Nor do they necessarily point to a set of criteria by which a system development program could be evaluated as to the degree to which systems engineering is followed. Despite the differences in detail and emphasis, philosophically they are the same. The same can be said about the different outlines of the system life cycle. Five versions from different authors and organizations are provided in Figure 1.1.

To be more specific and concrete, a list could be generated of the numerous tasks, tools, and techniques, both technical and managerial, that are considered "systems engineering" by different people and organizations, and such a list could enhance common understanding. Unfortunately, no one list would be agreeable to all people, even systems engineers. Furthermore, while there are many different tasks performed under the label of "systems engineering," some are not appropriate for application under all circumstances. Degree of task application, the formality in which the element is carried out, and how well the activity is performed are considerations affecting systems engineering effectiveness in a particular development process. Furthermore, the environment in which development occurs greatly impacts and can even determine the success or failure of system development by affecting the process itself. Additionally, the challenge and magnitude of the system design is another factor impacting system performance. Therefore, it is not possible to merely present a complete "laundry" list of systems engineering

Figure 1.1 System life cycle phases - different versions

<table>
<tr><td rowspan="2">Wymore</td><td rowspan="2">Requirements Development</td><td colspan="2" rowspan="2">Concept Development</td><td>Full-scale Engineering Development</td><td>Test and Integration</td><td rowspan="2">Operations, Support, and Modification</td><td rowspan="2">Retirement and Replacement</td></tr>
<tr><td colspan="2">System Development</td></tr>
<tr><td>DOD</td><td>Mission Need Identification and Definition</td><td>Concept Exploration</td><td>Demonstration/ Validation</td><td>Engineering and Manufacturing Development</td><td>Full Rate Production/ Deployment</td><td>Operational Support</td><td>Disposal/System Retirement</td></tr>
<tr><td>NASA</td><td>Conceptual Study</td><td>Concept Analysis</td><td>Concept Definition</td><td colspan="2">Design/Development</td><td>Operations</td><td></td></tr>
<tr><td>Pugh</td><td>Market User Needs and Demands</td><td>Product Design Specification</td><td>Concept Design</td><td>Detail Design</td><td>Manufacture/Sell</td><td colspan="2"></td></tr>
</table>

tasks, tools, and techniques and simply claim that if a systems development effort performs them all, success will result. Since design is an iterative process by which the elements of systems engineering are applied most effectively in a logical, disciplined manner throughout the life cycle of the system, development must be viewed and evaluated in several ways to obtain a clearer picture of the relationship between the results of system development and the characteristics of the process employed to get there.

Application of systems engineering principles and activities must be tailored to each particular system development effort. However, there are no known immutable, universal templates or algorithms for applying each and every systems engineering element. Much like designing a complex system itself, deciding on the implementation of systems engineering tasks, tools, and techniques involves many decisions requiring common sense and educated evaluation of numerous tradeoffs in order to achieve the best outcomes possible. Despite the qualitative judgments involved with applying and carrying out systems engineering, it is proposed that a credible methodology can be utilized to measure or rate its magnitude of application on development efforts already completed. The methodology can also be used to rate the magnitude of involvement of the other characteristics of system development, such as environment, design difficulty, and required resources. Using these results alone can be useful in

illustrating what systems engineering involves for the benefit of engineering students. However, these ratings might also be useful in empirically exploring the relationships among the system development process characteristics and the end results of an effort.

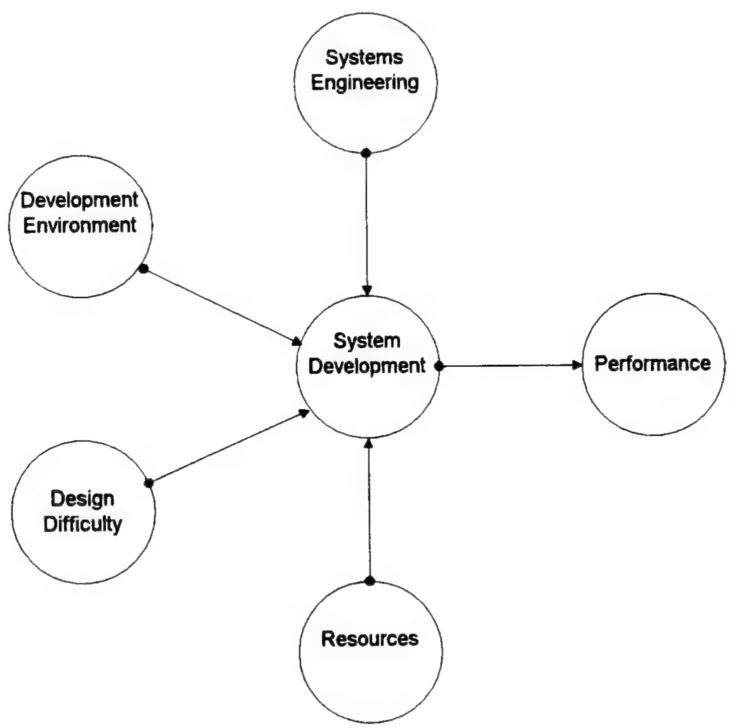
How, then, can a system development effort be evaluated as to the extent of systems engineering practices followed and their effectiveness as part of the design process? This thesis proposes the following approach. First, an evaluation methodology is developed through the creation of figures of merit and a rating scale for each of the five characteristics of a system development effort. These characteristics consist of (1) *performance* involving technical, cost, and schedule performance; (2) *systems engineering fundamentals* describing eleven crucial principles and practices that should be considered for application in any development; (3) eleven aspects of the *development environment* that are suggested to be conducive to supporting successful system development; (4) *design difficulty* consisting of six figures of merit addressing various aspects of technical complexity, and (5) *resources* in terms of cost, time and infrastructure to complete development. Within each characteristic, the figures of merit or elements are selected to be distinct and measurable and have a minimum amount of dependency between each other. Scoring criteria associated with each of the figures of merit and elements are generic, and

therefore they are appropriate for any type and size of system. This allows "apples-to-apples" comparisons of the quality of the development processes for different systems.

Second, these five characteristics are related to each other by the model in Figure 1.2. This basic representation shows that *systems engineering fundamentals*, *development environment*, *design difficulty*, and *resources* comprise a system development effort, and they interact to produce the *performance* outcomes. This simple model represents numerous complex interactions, but it does not describe how they occur. It is not known whether all or some of the characteristics are additive or multiplicative, or whether they can be combined at all. The major challenge is to attempt to understand how they react at a macro-level, if that is even possible. The hypothesis being pursued is that the characteristics can be rated with meaningful single numerical scores, thereby providing a shortcut means of analyzing the complex processes involved. Although the system development model is not a purely theoretically derived construct, there are sound bases for much of the descriptive model. For example, the *systems engineering fundamentals* figures of merit correspond to the managerial functions of planning, organizing, leading, controlling, and coordinating as defined in the Traditional Management School model. Furthermore, the *development environment* figures of merit correspond closely with many aspects of organizational theory.

Third, in order to demonstrate the ratings methodology and provide data for analysis, six case studies are presented and evaluated in accordance with the figures of merit rating criteria. The subject of the six cases is aircraft developed in the United States within the past 15 years. This topic was chosen because (1) aircraft are some of the most complex systems developed today, (2) a reasonably large number of companies develop aircraft and each does it differently, and (3) aircraft development is a somewhat mature process.

Figure 1.2 System Development Model



The fourth part of the approach is the compilation and analysis of the results. The individual scores of the figures of merit and elements are summed together to produce one numerical score for each of the five characteristics. This approach employs a simple multi-attribute rating technique. The resulting numbers are used in an attempt to uncover relationships among the characteristics, with particular emphasis on identifying a correlation between *systems engineering fundamentals* and the *performance* scores. The meaning of a relatively higher score for *performance* is not that one system is necessarily better than the other. Rather, it is a quality or success index of the development process itself.

The selection of the characteristics and their figures of merit were developed from a variety of sources. *Performance* incorporates the traditional measures (technical, cost, and schedule performance) of assessing the success of a development program. The *systems engineering fundamentals* represent the summarization and synthesis of a detailed list of principles, tasks, and techniques compiled from various systems engineering books and papers. (See references.) The *development environment* figures of merit were devised based on the author's experience as well as organizational studies (Quinn & Rohrbaugh, 1983; Elmes & Wilemon, 1992). They were also chosen based on their abilities to be measured to a reasonable degree. The elements and rating methodology for both *design difficulty* and *resources* were taken, with some modifications, from William L. Chapman's 1994 Ph.D.

dissertation at the University of Arizona, "The System Design Process is Intractable, But Robust." As part of his dissertation, he rated 18 case studies covering a wide range of efforts throughout history according to the two characteristics. He then plotted the cases on a two-axis graph to show how they compared to one another.

The approach and model design just presented can be viewed as logical, and they represent a first step towards systematically investigating the relationships among the high-level system development characteristics and the results of a development effort. However, there are a variety of questions and issues concerning the validity of the approach as related to the qualitative nature of many of the criteria, design of the numerical rating scale, independence of the figures of merit, subjectivity of the process, bias in the case studies, and mathematically combining the figures of merit scores.

First of all, the assignment of scores for the figures of merit and elements is based on rating criteria for all five system development characteristics, presented in Chapter 2. The topics addressed by the figures of merit for *systems engineering fundamentals* and *development environment* do not lend themselves to the formation of quantitative criteria for the most part. Instead, these criteria are mostly qualitative, and many of them are imprecise. Given the complexity of the topics being

evaluated, the criteria must be at a very high level or else be made extremely detailed. Making them detailed reduces their usefulness for educational purposes.

The zero to ten point scale used in a majority of the figures of merit rating criteria was selected because it allows easy separation of ratings into three ranges of high, medium, and low. Given the qualitative nature of most of the criteria, subjective judgments can be easily assigned among three categories based on a reasonable amount of information provided to the evaluator. Furthermore, allowing the choice of several points within each of the three categories provides the rater the ability to score with greater fidelity if the degree of information detail is provided.

While the case studies were researched rather extensively, the information gathered was obtained from limited sources. Therefore, there may be unintended biases, omissions, or inaccuracies which may impact the ratings for particular figures of merit.

An issue of fundamental importance is whether or not the proposed figures of merit ratings summed into single higher level characteristic scores have validity and significance as generic measures, thereby allowing meaningful comparison between systems. This issue depends on the degree of dependence between the figures of merit within a characteristic, the extent to which the

figures of merit and elements completely define the factors at work within a characteristic, and the appropriateness of the relative weighting within each characteristic. While some dependencies do exist between the figures of merit, most can be considered as minimal based on a simple cause-effect analysis. Also, the characteristics can be reasonably regarded as not leaving out major high-level factors since the figures of merit address all the major areas identified in appropriate literature.

The scoring method for the first three characteristics assumes that most figures of merit have equal weight within, since the relative importance of each is not understood in a quantitative way. The hope is that insights into relative weighting may be gained by applying the approach outlined in this thesis to a sufficiently large number of cases. The exceptions to the equal weighting assumption are the first two figures of merit in the *systems engineering fundamentals* characteristic. They are each weighted twice their ratings based on studies that have shown that the majority of the life cycle cost of a system is determined in the requirements and concept development phases. [Zangwill, 1992] Of all the figures of merit in the *systems engineering fundamentals* characteristic, these two are most associated with the early phases of a program. While this overall weighting structure does warrant further investigation and refinement, it is meant to be a starting point.

An important point to make is that this thesis is not attempting to explore in detail the combinatorial issues surrounding the summation of the ratings. While there is a huge amount of literature dealing with mathematical and behavioral aggregation and multi-criteria decision making, delving into those issues would take this thesis beyond what is needed at this point in the development of the approach. Instead, as mentioned previously, the figures of merit are believed to be reasonably independent, thereby supporting the basic validity of the approach. Furthermore, only simple graphical analysis techniques are used to analyze the data generated. Due to the low number of data points generated, sophisticated statistical methods are of minimal usefulness.

While the focus of this thesis is systems engineering and its impact in the system development process, there is some relation to the area of organizational effectiveness. Although the model and analysis method presented are not oriented towards any specific organizational structure, they take into account organizational factors in the *systems engineering fundamentals* and *development environment* characteristics. In fact, some of the *development environment* figures of merit correspond almost directly with organizational effectiveness measures.

Many studies have been conducted attempting to determine, measure, and evaluate the characteristics of successful

organizations, and many case studies have been developed describing successful and unsuccessful products and how they were developed. Furthermore, studies of the effectiveness of concurrent engineering, a development approach which can be viewed as good systems engineering, identify most of the same types of issues addressed in the systems engineering fundamentals. (See Zangwill, 1992.) However, to the author's knowledge, none have structured the development process in the same way as presented in this thesis or attempted to uncover high level relationships between characteristics of system development. Furthermore, no other studies have identified *systems engineering fundamentals* as recognizable elements that can be evaluated as a group and represented with a single numerical rating. This thesis proposes such a methodology.

The outline of the evaluation methodology showing the system development characteristics and lists of the figures of merit are presented in the following sections.

**Performance**

*Performance* is composed of measures used to assess the degree of success of the overall development process of a system. The figures of merit consist of the following:

A. Technical performance at initial deliveries.

B. Technical performance one to two years after delivery.

C. Cost performance during full-scale engineering development (FSED).

D. Schedule performance during FSED.

**Systems Engineering Fundamentals**

The approach to measure the degree of system engineering followed during development involves identifying a top-level list of key principles, activities and tasks that should be considered during any development program of reasonable complexity. This approach is in contrast to trying to develop a detailed, all encompassing list. As part of the rating process for each case study, the fundamental systems engineering practices are evaluated as to whether or not they were accomplished, to what extent they were completed, and how well these fundamental elements were carried out. This involves not just the issue of completeness and the expertise displayed, but also the appropriateness of application and the proper timing in which system engineering elements are applied and carried out.

The following is a list of fundamental practices or elements of good systems engineering. In the author's opinion, all are accomplished as part of effective systems engineering. However, the extent and formality of the application depends on the particulars of the system being developed. The tasks associated with these figures of merit are not necessarily performed by

officially designated systems engineers:

A. Requirements development.

B. Incipient system design.

C. Evaluating alternative concepts and designs.

D. Make-or-buy decision.

E. Validation.

F. Verification and integrated testing.

G. Configuration management.

H. Manufacturing considerations.

I. Systems integration and technical management.

J. Life cycle considerations.

K. Program management.

**Development Environment**

The third aspect of evaluating the systems development process is the environment in which it takes place. The environment is probably an equally crucial factor for success. Even expertly performed systems engineering practices can be overcome by negative environmental factors. However, a positive environment cannot make up for inadequate or poorly performed systems engineering. Both *systems engineering fundamentals* and *development environment* work together and impact each other in complex ways.

Most of the elements of this third aspect are beyond the direct control of the systems engineer, chief engineer, and the program manager. Some are under the control of those in authority above the effort or totally external to it. However, if these elements are favorable, they can enhance the effectiveness of systems engineering practices and contribute to development success. They are as follows:

A. Emphasis on the customer.

B. Stability of requirements and configuration.

C. Funding and workforce-level stability.

D. Strong support of program.

E. Continuity of core development team.

F. Stability of organizational structure.

G. Cooperation among all stakeholders.

H. Effective communication within team.

I. Flexibility and autonomy.

J. Workforce expertise and experience.

K. Accountability for system performance.

**Design Difficulty**

*Design difficulty* essentially represents different aspects of technical complexity and scope of effort. The following is a list of the elements:

A. Design type.

B. Knowledge complexity.

C. Steps (needed to complete the design).

D. Quality implementation effort.

E. Extent of manufacturing operations.

F. Selling price constraint.

**Resources**

The *resources* characteristic refers to those items needed to complete the design, test, and fabrication of the system. The following is a list of the *resources* elements:

A. Cost.

B. Time.

C. Infrastructure.

In the next chapter, a description for each figure of merit and element and the methodology for evaluating and rating a system development effort are presented. The methodology involves criteria and scoring rules developed for each figure of merit and element, and it results in a single number score for each of the five characteristics.

# CHAPTER 2

# EVALUATION AND SCORING METHODOLOGY

This chapter contains the methodology for evaluating system design case studies and assigning quantitative scores to them. The five development effort characteristics are presented with the figures of merit or elements which define them as well as the criteria for assigning scores. The figures of merit scores for each case are added together, resulting in a single numerical score for each of the characteristics. The first three characteristics presented, *performance*, *systems engineering fundamentals*, and *development environment*, are positive measures, in that the higher the score, the better. The *design difficulty* and *resources* characteristics, however, merely describe the system design and do not reflect relative "goodness" of the design effort or the design.

**Performance**

A. Technical performance - initial. This is defined as compliance with customer performance requirements and specifications and overall customer satisfaction at time of initial system deliveries.

- 7-10 points are given for a highly successful system, in that the system achieves all or nearly all key technical performance requirements at time of initial system delivery. There is a high degree of customer satisfaction.

- 4-6 points are given for a moderately successful system, in that the system meets a majority of key technical performance requirements, rendering it useful to the customer. However, operational performance of some subsystems is less than expected. The result is a moderate degree of customer satisfaction.

- 0-3 points are given for an unsuccessful system, in that the system fails to meet significant technical performance requirements at time of initial system delivery, rendering it unusable by the customer as originally intended. The result is low customer satisfaction.

B. Technical performance - mature. This is defined as compliance with customer performance requirements and specifications and overall customer satisfaction, one to two years after system delivery.

- 7-10 points are given for a highly successful system, in that the system achieves all or nearly all key technical performance requirements. There is a high degree of customer satisfaction.

- 4-6 points are given for a moderately successful system, in that the system meets a majority of key technical performance requirements rendering it useful to the customer. The result is a moderate degree of customer satisfaction.

- 0-3 points are given for an unsuccessful system, in that the system fails to meet significant technical performance requirements, rendering it unusable by the customer as originally intended.

C. Cost performance. This deals with how close the full-scale engineering development (FSED) effort meets the budget; production costs are not considered. This is measured using percentage cost growth (overrun) of the original FSED baseline estimate. This measure is from the point of view of the funding source.

- 9-10 points are given for an effort conducted below the baselined development cost requirement to no more than 5 percent cost growth (overrun).
- 7-8 points are given for an effort with 6 to 15 percent cost growth (overrun) of the baselined development cost requirement.
- 5-6 points are given for an effort with 16 to 35 percent cost growth (overrun).
- 3-4 points are given for an effort with 36 to 75 percent cost growth (overrun).
- 0-2 points are given for an effort with greater than 75 percent cost growth (overrun).

D. Schedule performance. This is defined as the percentage of time that the FSED effort is overdue, with the effort defined to take place from the start of FSED to the delivery to the customer of the first production unit. This is determined by taking the length of time from the start of FSED to planned customer delivery of the first production unit (planned FSED length), taking the length of time from the start of FSED to the actual delivery of the first unit, take the difference between the two (assuming the actual is longer than the planned length), and dividing the difference by the planned FSED length.

- 9-10 points are given for on-time performance or not more than 2 percent overdue (baselined development schedule).
- 7-8 points are given for 3 percent or more overdue but less than 10 percent overdue.
- 5-6 points are given for 10 percent or more overdue but less than 20 percent overdue.
- 3-4 points are given for 20 percent overdue or more but less than 50 percent overdue.

- 0-2 points are given for 50 percent or more overdue.

The ratings and scores are provided in a table at the end of each case study similar to that illustrated in Table 2.1.

Table 2.1 Performance scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| TECHNICAL PERFORMANCE - INITIAL | 0-10 | 1 | | |
| TECHNICAL PERFORMANCE - MATURE | 0-10 | 1 | | |
| COST PERFORMANCE | 0-10 | 1 | | |
| SCHEDULE PERFORMANCE | 0-10 | 1 | | |
| PERFORMANCE TOTAL | | | | 0-40 |

**Systems Engineering Fundamentals**

A. Requirements development. This is defined as understanding customer needs, properly stating the problem, and accurately specifying the requirements that define what the system must do.

- 7-10 points are given for accurate and thorough understanding and documentation of the customer's problems and needs, and for the documentation of system-level requirements in a single specification.

- 4-6 points are given for reasonably accurate and thorough understanding of the customer's problems and needs in a requirements document, but significant adjustments are required.

- 0-3 points are given for inaccurate and incomplete definition of the customer's problems and needs.

B. Incipient system design. This consists of defining system concept models at the beginning of the effort, identifying and organizing the hierarchy of functions (functional decomposition) to be performed by the system based on the top-level performance objectives, defining the system constraints and interfaces, defining the hierarchy of physical elements (physical decomposition), and allocating detailed performance and interface requirements to the physical elements (subsystems).

- 7-10 points are given for clearly defined top-level system concept models that are decomposed into functions or elements, with well defined interfaces and detailed requirements allocations to the decomposed items. Furthermore, these are completed before FSED.

- 4-6 points are given for marginally defined top-level system concept models that are decomposed into functions or elements, with adequately defined interfaces and requirements allocations to the decomposed items. Furthermore, these are completed before FSED.

- 0-3 points are given for inadequate top-level modelling of the system concept, insufficient or inappropriate interface definitions, and poor requirements allocation, or the failure to adequately complete such activities before FSED.

C. Evaluating alternative concepts and designs. This refers to evaluating the relative merit of alternative concepts and designs using a design tradeoff methodology (formal or informal) that uses results of analyses, simulation model testing and/or physical model testing.

- 7-10 points are given for thoughtfully evaluating and deciding among alternative concepts and/or subsystem designs using a formal or informal design tradeoff methodology utilizing results of analyses, simulation model testing and/or physical model testing.

- 4-6 points are given for limited consideration and analysis of alternative concepts and subsystem designs using a formal or informal design tradeoff methodology utilizing results of analyses, simulation model testing and/or physical model testing.

- 0-3 points are given for little or no consideration and analysis of alternative concepts and subsystem designs.

D. Make-or-buy decision. This is the act of determining whether a subsystem or component of the system should be developed and built by the system developer (in-house) or purchased from a source outside of the system developer's group based on criteria such as cost, time, and the item's technical performance. This does not covers subsystems and components that the system developer has decided a priori not to perform a make-or-buy evaluation based on the development philosophy, company expertise and background, or security classification. (For example, an aircraft integrator without experience in developing and building jet engines would not consider developing and building them in-house for a new aircraft. The development approach would be to obtain them from sources with specialties in jet engines.)

- 7-10 points are given for performing make-or-buy evaluations and decisions regarding a majority of a system's subsystems and components that are not already covered by a reasonable a priori development policy reflecting the system developer's in-house capabilities and resources.

- 4-6 points are given for performing make-or-buy evaluations and decisions regarding some of the system's subsystems and components that are not already covered by a reasonable a priori development policy reflecting the system developer's in-house capabilities and resources.

- 0-3 points is given for little or no consideration of the

tradeoffs between developing subsystems and components in-house and purchasing them from outside.

E. Validation. This consists of the validation of requirements to ensure they are consistent with the customers' needs and that a real world solution can be built and tested to prove that it satisfies the requirements.

- 7-10 points are given for conducting a methodical process involving direct interaction with the customer to ensure the system requirements are consistent with the true needs of the customer, and determining that a real world solution can be built and tested.
- 4-6 points are given for ensuring the requirements are consistent with the true needs of the customer through indirect methods, such as referencing marketing surveys, and for determining that a real world solution can be built and tested.
- 0-3 points for not reviewing requirements with regard to actual customer desires or not attempting to justify that a real world solution exists.

F. Verification and integrated testing. This figure of merit refers to the determination of design compliance with performance specifications and the determination of as-built hardware and software compliance with specification and drawing requirements. This includes identifying component-level to system-level testing in a test and evaluation master plan early in development. It also refers to actually conducting tests and inspections in a complete and logical manner of components and subsystems individually, then of combinations of components and subsystems together, and finally of the final integrated system.

- 7-10 points are given for a complete job of verifying design and hardware/software compliance with specifications and drawings, clearly identifying early in development the planned component, subsystem, and system-level testing in a comprehensive test plan, and then actually conducting the testing.

- 4-6 points are given for partially verifying design and hardware/software compliance with specifications and drawings, incompletely identifying early in development the planned component, subsystem, and system-level testing in a test plan or series of plans, and then eventually conducting all the needed testing.

- 0-3 points are given for incomplete, inadequate attempts to verify design and hardware/software compliance with specifications and drawings, not planning for and identifying early in development the progression of tests from component-level to system-level throughout system development, and not conducting important tests.

G. Configuration management. This refers to establishing and maintaining the status of the design configuration and interfaces and as defined by specifications and drawings (paper or digital), controlling changes to the configuration, appropriately controlling changes between subsystems and between the system and the external world, and maintaining the traceability of the configuration as it changes.

- 7-10 points are given for effectively controlling interface changes within a formal system, maintaining accurate status of the design configuration, controlling configuration changes through a formal system of review, approval, and update, and maintaining the traceability of the configuration.

- 4-6 points are given for controlling interface changes within a formal system with some problems, maintaining reasonably accurate status of the design configuration, controlling configuration changes with some difficulty, and maintaining reasonable traceability of the configuration.

- 0-3 points are given for inadequately controlling interface changes, failing to maintain accurate status of the design

configuration, inadequately controlling configuration changes, and/or not maintaining traceability of the configuration.

H. Manufacturing considerations. This is defined as addressing and giving priority to appropriate manufacturing considerations early in system development with the objectives of having (1) the manufacturing entity have adequate time to prepare for fabrication and production and (2) the manufacturing considerations influence the design of the system and its manufacturing processes to reduce fabrication costs.

- 7-10 points are given for developing manufacturing processes concurrently with the system design, and allowing the design to be significantly influenced by manufacturing considerations to improve ease and/or cost of fabrication.
- 4-6 points are given for involving manufacturing personnel early in development, but not allowing the design to be significantly influenced by them to improve ease and/or cost of fabrication.
- 0-3 points are given for ignoring or placing low emphasis on manufacturing issues during system design.

I. Systems integration and technical management. This function involves bringing subsystems together to produce the desired results and ensure that the subsystems will interact to satisfy the customers' needs. This involves:

- organizing the technical effort; identifying how the development will be broken out and managed
- integrating activities of the development team; balancing the influence of all required design specialties;

resolving design conflicts

- ensuring compatibility of all physical, functional, and program interfaces
- assessing and managing technical risk

- 7-10 points are given for effectively bringing subsystems together through a well organized and integrated technical effort that balances the influence of all required design specialties.
- 4-6 points are given for bringing subsystems together with significant difficulty, due to inadequate subsystem verification or problems in the organization of the technical activities which does not thoughtfully balance the influence of all required design specialties.
- 0-3 points are given for failing to effectively bring subsystems together.

J. Life cycle considerations. This refers to giving priority to long term issues, such as supportability (primarily maintainability, reliability, and training) and life cycle costs consistent with appropriate system requirements and objectives.

- 7-10 points are given for fully recognizing and addressing supportability and life cycle cost requirements and issues early in development.
- 4-6 points are given for recognizing and minimally addressing supportability and life cycle cost requirements and issues early in development.
- 0-3 points are given for not adequately recognizing and addressing supportability and life cycle cost requirements and issues early in development.

K. Program management. This involves the planning, tracking, and coordination of activities performed by all elements of the

development team as well as the resolution of impediments to program progress. Evidence of strong program management include an integrated master scheduling system, an efficient cost accounting system which provides management visibility into development activities in a timely manner, life cycle cost estimates, risk analyses, and the conduct of regular program reviews involving all the key stakeholders.

- 7-10 points are given for a strong program management function that effectively keeps the effort on track through use of an accurate integrated master scheduling system, use of a cost accounting system providing timely information, and holding regular program reviews with program stakeholders.

- 4-6 points are given for a program management function of medium strength that keeps the effort only moderately on track due at least partly to problems with the management support systems and practices.

- 0-3 points are given for a weak program management function that does not keep the effort on track and has deficient management support systems and practices.

The ratings and scores are provided in a table at the end of each case study similar to that illustrated in Table 2.2.

Table 2.2 Systems Engineering Fundamentals scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| REQUIREMENTS DEVELOPMENT | 0-10 | 2 | | |
| INCIPIENT SYSTEM DESIGN | 0-10 | 2 | | |
| EVALUATING ALTERNATIVE CONCEPTS AND DESIGNS | 0-10 | 1 | | |
| MAKE-OR-BUY DECISION | 0-10 | 1 | | |
| VALIDATION | 0-10 | 1 | | |
| VERIFICATION AND INTEGRATED TESTING | 0-10 | 1 | | |
| CONFIGURATION MANAGEMENT | 0-10 | 1 | | |
| MANUFACTURING CONSIDERATIONS | 0-10 | 1 | | |
| SYSTEMS INTEGRATION AND TECHNICAL MANAGEMENT | 0-10 | 1 | | |
| LIFE CYCLE CONSIDERATIONS | 0-10 | 1 | | |
| PROGRAM MANAGEMENT | 0-10 | 1 | | |
| SYSTEMS ENGINEERING FUNDAMENTALS TOTAL | | | | 0-130 |

**Development Environment**

A. Emphasis on the customer. The customer requirements are the primary design drivers, and user input during the entire development process is accepted and encouraged.

- 7-10 points are given for a high emphasis on receiving and positively responding to direct or indirect customer involvement throughout development.
- 4-6 points are given for a moderate emphasis on receiving and positively responding to direct or indirect customer involvement throughout development.
- 0-3 points are given for little or no emphasis on receiving

or positively responding to inputs from the customer throughout development.

B. Stability of requirements and configuration. The customer requirements do not undergo a series of major changes after the start of FSED, and the system configuration does not undergo numerous alterations, whether they are driven by customer requirements changes or correction of design deficiencies.

- 7-10 points are given for minor changes to no change in customer requirements and/or for a low number of moderate configuration changes during FSED.
- 4-6 points are given for moderate changes in customer requirements and/or for a low number of major configuration changes during FSED.
- 0-3 points are given for major changes in customer requirements and/or for a moderate to large number of major configuration changes during FSED.

C. Funding and workforce-level stability. This means that the development effort follows a multi-year budget that does not change significantly each year from original plan. Furthermore, the workforce-level throughout FSED follows a long-term plan.

- 7-10 points are given for no unplanned, major dips or spikes in funding amounts and workforce-levels throughout FSED.
- 4-6 points are given for moderate funding and workforce-level deviations from long term plans during FSED.
- 0-3 points are given for major and severe funding and workforce-level deviations from long term plans during FSED.

D. Strong support for program. This is defined as a development effort having strong general support within its company (referring to commercial programs) or within the government, public and media (referring to government programs) during FSED.

- 7-10 points are given for strong support throughout concept development and FSED with no significant controversy threatening viability of the effort.
- 4-6 points are given for moderate support or sharply contrasting levels of support during concept development and FSED due to significant controversy that moderately threatens the viability of the effort.
- 0-3 points are given for little or no support resulting from a significant controversy during concept development and FSED that seriously threatens the viability of the program.

E. Continuity of core development team. This means that a core team of designers and managers remaining throughout development; there is minimal turnover of key personnel.

- 7-10 points are given for there being only little or no turnover of key designers and managers during concept development and FSED.
- 4-6 points are given for there being a moderate amount of turnover of key designers and managers during concept development and FSED.
- 0-3 points are given for essentially little or no continuity of key designers and managers during concept development and FSED.

F. Stability of organizational structure. This means that the system development organization does not go through major reorganizations during the development of the system.

- 7-10 points are given for the development group not going through a major reorganization during FSED.
- 4-6 points are given for the development group going through a moderate reorganization during FSED.
- 0-3 points are given for the development group going through a major reorganization during FSED.

G. Cooperation among all stakeholders. This refers to the existence of positive, non-confrontational working relationships among the team members and between the team members and the customer(s). Furthermore, there are no major hidden agendas in conflict with program and customer objectives.

- 7-10 points are given for very positive, non-confrontational working relationships among program participants during FSED.
- 4-6 points are given for generally positive to generally negative working relationships existing among program participants during FSED.
- 0-3 points are given for very negative working relationships among program participants that severely impede or stop program progress during FSED.

H. Effective communication within team. This is defined as how well members of the development team (including subcontractors and customers) communicate and coordinate among themselves. It is evidenced by adequate mechanisms for communication, such as close physical proximity of the workers to each other or the existence and use of communication mechanisms such as telephones, fax machines, computer aided design/manufacturing systems, and computer networks. It is also influenced by the

organizational structure, the management philosophy, and cultural factors of the organization.

- 7-10 points are given for effective communication and coordination among the development team members and between them and the customers.
- 4-6 points are given for moderately effective communication and coordination among the development team members and between them and the customers.
- 0-3 points are given for ineffective communication and coordination among the development team members and between them and the customers due to poor circumstances and mechanisms.

I. Flexibility and autonomy. This refers to the ability to implement design changes quickly, thereby not being significantly hindered by organizational or procedural roadblocks. Flexibility and autonomy is evidenced by fast and efficient design change mechanisms and by the absence of bureaucratic (government or corporate) micromanagement of development activities.

- 7-10 points are given for the ability to make decisions and implement design changes quickly without procedural roadblocks or bureaucratic micromanagement.
- 4-6 points are given for a moderate degree of procedural impediments to quick decision making and change implementation, due to inflexible and inefficient procedures and/or micromanagement of development activities by corporate or government bureaucracy.
- 0-3 points are given for significant procedural impediments to quick decision making and change implementation and/or a large amount of micromanagement of development activities by corporate or government bureaucracy.

J. Workforce expertise and experience. This means that development personnel have appropriate skills and experience to enable development success.

- 7-10 points are given for most development team members being highly skilled and experienced in appropriate areas.
- 4-6 points are given for a moderate number of development team members being skilled in appropriate areas, but lacking experience.
- 0-3 points are given for a severe lack of appropriate skills and expertise among development team.

K. Accountability for system performance. This means that the system developer is held accountable to the customer for the performance of the resulting system. Such a situation is evidenced by the existence of mechanisms such as warranties and product liability laws. Another factor is the importance of reputation to the developer, as well as the significance of reputation to future efforts. Accountability for system performance also means that the system developer is responsible to its funding source for the way the effort is conducted, and this is evidenced by award fee and incentive fee structures for cost type government contracts, bonus programs for commercial efforts, and mechanisms for quickly replacing personnel if progress is not satisfactory.

- 7-10 points are given for strong warranties on key performance parameters and defective parts, for award and bonus fee mechanisms, for product liability laws, and/or strong motivation to maintain company reputation.
- 4-6 points are given for warranties covering the replacement of defective parts and excluding some key performance parameters, in addition to limited award fee or bonus

mechanisms and product liability laws.

- 0-3 points for no warranty or extremely limited warranty covering replacement of defective parts and no other significant accountability mechanisms in place.

The ratings and scores are provided in a table at the end of each case study similar to that illustrated in Table 2.3.

Table 2.3 Development Environment scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| EMPHASIS ON THE CUSTOMER | 0-10 | 1 | | |
| STABILITY OF REQUIREMENTS AND CONFIGURATION | 0-10 | 1 | | |
| FUNDING AND WORKFORCE-LEVEL STABILITY | 0-10 | 1 | | |
| STRONG SUPPORT FOR PROGRAM | 0-10 | 1 | | |
| CONTINUITY OF CORE DEVELOPMENT TEAM | 0-10 | 1 | | |
| STABILITY OF ORGANIZATIONAL STRUCTURE | 0-10 | 1 | | |
| COOPERATION AMONG ALL STAKEHOLDERS | 0-10 | 1 | | |
| EFFECTIVE COMMUNICATION WITHIN TEAM | 0-10 | 1 | | |
| FLEXIBILITY AND AUTONOMY | 0-10 | 1 | | |
| WORKFORCE EXPERTISE AND EXPERIENCE | 0-10 | 1 | | |
| ACCOUNTABILITY FOR SYSTEM PERFORMANCE | 0-10 | 1 | | |
| DEVELOPMENT ENVIRONMENT TOTAL | | | | 0-110 |

**Design Difficulty**

A. Design type reflects whether feasible solutions exist and how much original thought goes into the project.

- 14 or 15 points are given for a breakthrough design effort.
- 7-13 points are given for original innovative design.
- 0-6 points are given for continuous improvement.

B. Complexity of the knowledge needed to create the design is determined based on an estimate of the number and availability of the people with the necessary knowledge to do the design.

- 9 or 10 points are given for undiscovered knowledge that can found only by specialists.
- 6-8 points are given for complex knowledge held by few people.
- 3-5 points are given for complex knowledge held by a sufficient pool of people
- 0-2 points are given for common knowledge held by many people.

C. The number of steps needed to complete the design is defined as the number of discrete steps needed to design the system. It is related to the number of major components or major process steps that are needed to assemble the system.

- 9 or 10 points are given for systems with greater than 10,000 steps or components.
- 5-8 points are given for systems with more than 500 but less than 10,000 steps or components.
- 3 or 4 points are given for systems up to 500 steps or components.

- 0-2 points are given for any system with fewer than 50 steps or components.

D. Quality implementation effort refers to the extent to which the company designing and building the system follows advanced quality programs and practices, such as total quality management (TQM), ISO-9000, Baldridge Award criteria, Six Sigma, Taguchi methods, and Quality Function Deployment (QFD).

- 7-10 points are given for a system whose developer places high emphasis on implementing or continuing quality-related programs and techniques on the system development effort.
- 4-6 points are given for a system whose developer places medium emphasis on implementing or continuing quality-related programs and techniques on the system development effort.
- 0-3 points are given for a system whose developer places little or no emphasis on implementing or continuing quality-related programs and techniques.

E. Manufacturing operations implementation effort addresses the combination of the complexity of the fabrication processes and the quantity of the items produced. For example, the manufacturing arrangement to produce one or a few large, complex systems can be as extensive as those established to mass produce small, less complex systems. Quantity is normalized between different items by partly basing the measure on the extent of national market share met by the output of a system's manufacturing operations.

- 5 points are given for highly complex manufacturing operations that are designed to produce systems in quantities to meet a large national market share.

- 4 points are given for:
  (1) highly complex manufacturing operations that are designed to produce systems in quantities to meet a moderate national market share, or
  (2) manufacturing operations of moderate complexity that are designed to produced systems in quantities to meet a large national market share.

- 3 points are given for:
  (1) highly complex manufacturing operations that are designed to produce systems in quantities to meet a small national market share, or
  (2) manufacturing operations of moderate complexity that are designed to produce systems in quantities to meet a moderate national market share, or
  (3) manufacturing operations of low complexity that are designed to produce systems to meet a large national market share.

- 2 points are given for:
  (1) manufacturing operations of moderate complexity that are designed to produce systems in quantities to meet a small national market share, or
  (2) manufacturing operations of low complexity that are designed to produce systems in quantities to meet a moderate national market share.

- 1 point is given for manufacturing operations of low complexity that are designed to produce systems in quantities (of greater than one unit) to meet a small national market share.

- 0 points are given for manufacturing operations of low complexity that are designed to produce only one system, meeting only a small national market share.

F. Selling price constraint is defined as the degree to which the system design is driven and constrained by unit sales price requirements or goals. These requirements and goals are set based on the competition level in the market. In general, the greater the competition, the greater the constraint. The sales price requirements and goals for government systems can be determined by design-to-cost requirements or goals as well as

by the existence of equivalent commercial systems already on the market.

- 4-5 points are given for very challenging unit sales price requirements or goals driven by a highly competitive market.
- 2-3 points are given for moderately challenging unit sales price requirements or goals driven by a moderately competitive market.
- 0-1 points are given for little or no challenge to meet unit sales price requirements or goals due to lack of competition or no unit sales price requirements or goals exist.

The scores are provided in a table at the end of each case study similar to that illustrated in Table 2.4.

Table 2.4 - Design Difficulty scores.

| Element | Range | Score |
|---|---|---|
| TYPE | 0-15 | |
| KNOWLEDGE COMPLEXITY | 0-10 | |
| STEPS | 0-10 | |
| QUALITY IMPLEMENTATION EFFORT | 0-10 | |
| MANUFACTURING OPERATIONS IMPLEMENTATION EFFORT | 0-5 | |
| SELLING PRICE CONSTRAINT | 0-5 | |
| DESIGN DIFFICULTY TOTAL | 0-55 | |

**Resources**

A. Cost is the amount needed to pay for development, including salaries, utilities, supplies, and materials, through the first production unit. This is not in absolute dollars, but in

terms of the payer's ability to pay. For example, it is easy for a rich man to afford a VAX computer, but not a person with an average salary. Combine 1,000 average salaries and these people can afford a VAX.

- 14 or 15 points are given for massively expensive systems requiring major sacrifices.
- 9-13 points are given for very expensive systems that are developed rarely.
- 3-8 points are given for moderately expensive systems.
- 0-2 points are given for affordable systems.

B. The time score is for time spent from the beginning of the effort to define the customer's needs through the first production unit.

- 10 points are given for more than eight years.
- 8 or 9 points are given for up to eight years.
- 4-7 points are given for up to five years.
- 3 points are given for a year.
- 2 points are given for three months to around six months.
- 1 point is given for a month to less than three months.
- 0 points are given for less than a month.

C. Infrastructure required to achieve the design is also hard to quantify. Infrastructure is described as physical resources needed for construction (including machine tools, process shops, and assembly workstations), transportation, communication, utilities, laws and legal protections, skilled managers, and the education system available.

Infrastructure must be judged in regard to the designer's ability to get and use the infrastructure over the needed design time.

- 9 or 10 points are given for a massive infrastructure requiring major portions of the available labor force and the available equipment.
- 6-8 points are given for large complex infrastructures requiring large portions of the cost of the entire project
- 3-5 points are given for moderate infrastructures requiring people on the project to support it.
- 0-2 points are given if it is a common, low cost infrastructure (e.g. clean tap water in the U.S.)

The scores are given in a table at the end of each case study similar to that illustrated in Table 2.5.

Table 2.5 Resources scores.

| Element | Range | Score |
|---|---|---|
| COST | 0-15 | |
| TIME | 0-10 | |
| INFRASTRUCTURE | 0-10 | |
| RESOURCES TOTAL | 0-35 | |

**Explanation of Scoring**

Each case in Chapter 3 is evaluated using the rating and scoring methodology above. After ratings are assigned to the individual figures of merit and elements, they are totaled for each

development effort characteristic (*performance*, *systems engineering fundamentals*, *development environment*, *design difficulty*, and *resources*).

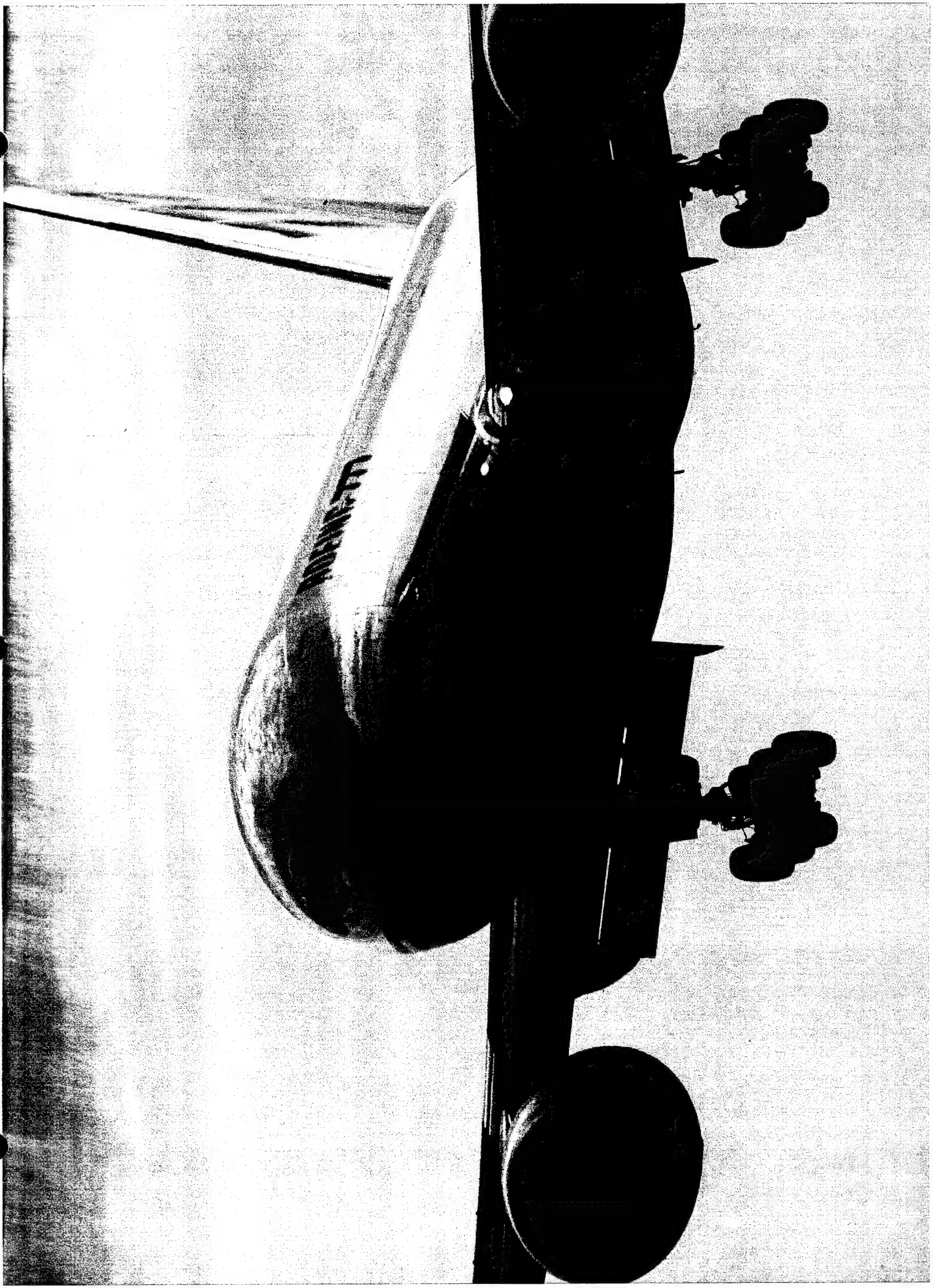
The final scores reported in this thesis were determined by the author using inputs from nine engineers who individually read and rated the case studies. The final scores, however, are not the averages of those from the different individuals. These final case study scores are compiled and analyzed in Chapter 4.

The case study evaluations by the nine engineers were primarily used to help perform an initial validation of the evaluation methodology by identify weaknesses in the case studies and the ratings criteria. Based on the mean and variability of the group's scores, the author improved passages in case studies, strengthened the wording and content of some rating criteria, and modified inappropriate scores. The validation data is presented and discussed in Chapter 5.

# CHAPTER 3

# CASE STUDIES

The sources of information used in the preparation of the following six case studies included periodicals, questionnaires, interviews, reports, books, and brochures. References are presented at the end of each case. A sample questionnaire is included in the Appendix.



## 3.1 CASE STUDY: BOEING 777 COMMERCIAL TRANSPORT

The Boeing 777 is the world's largest twin-engine commercial transport currently being developed for long distance commercial passenger and cargo travel. It is intended to fill a market and product gap between Boeing's 767-300 and the 747-400 jumbo jet, and it will compete directly against the McDonnell Douglas MD-11 trijet and the four-engine Airbus Industrie A330/340 family. The 777 is unique in that it was developed in a significantly different manner than the earlier Boeing aircraft, and even its competitors. Three characteristics of this development were (1) multi-disciplinary teams working together to concurrently design the aircraft and its production processes, (2) an unprecedented participation of the customer airlines in the development process, and (3) the design and integration work being done almost entirely on computer. All of these innovations were intended to produce an aircraft that was free of problems and ready for full service when delivered to the customer.

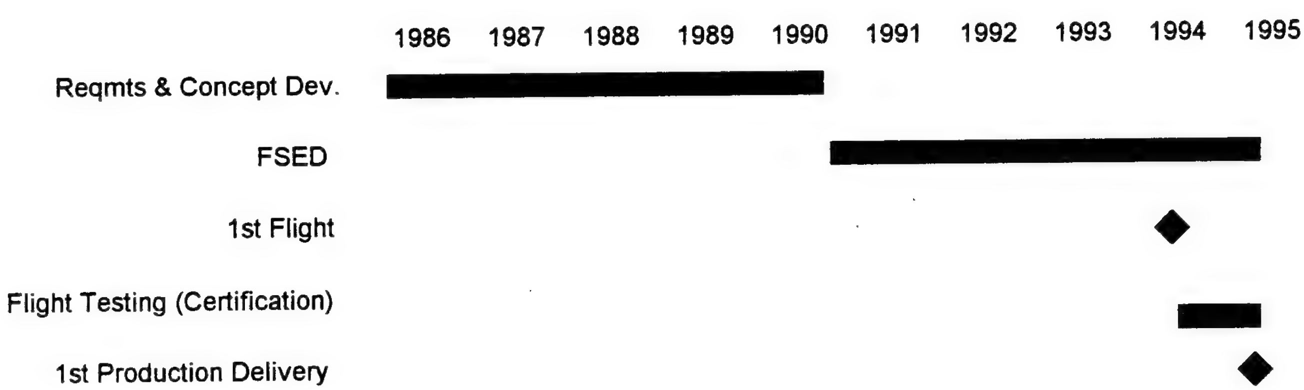
### Development History, Design, and Performance Outcomes

The Boeing Company officially launched the 777 development program on October 29, 1990, when its corporate board of directors gave approval to take what was then a concept development effort into full-scale engineering development (FSED) and production. Despite some problems with engine development,

the effort progressed according to plan. The first flight took place according to original schedule on June 12, 1994, and flight testing to certify the three different engines available to customers is expected to run through March 1996. Boeing made its first 777 delivery to United Airlines on schedule in May 1995. (See Figure 3.1.)

As of late 1994, there were 147 firm orders and 108 options for the $125 million transports. While the primary financing has come from Boeing, the Japanese companies that are fabricating large portions of the fuselage planned to put up from 8-10 percent of the estimated $4 to $5 billion start-up costs. [O'Lone, 1990]

Figure 3.1 777 development schedule




The 777 can be regarded as an original design. However, it can also be described as a major redesign that is evolutionary in nature since the design is based primarily on experience gained

from the Boeing 757 and 767 introduced in the early 1980s and the latest version of the 747 introduced in 1989. The 777 has the appearance of an enlarged 767, and several major items were taken from the 757, 767, and 747-400. For example, the nose structure of the 777 is the same as the 767. The cockpit design was derived from the 747-400. The engine attachment is a scaled version of the design used on the 757. Also, one of the three engines that will be certified with the 777, the Pratt and Whitney PW4074, is a larger derivative of the existing PW4060 used on the 767. In addition to using subsystems and components from earlier aircraft, the 777 utilizes a significant amount of advanced technologies both inside and out to meet challenging performance and design goals.

The primary 777 goal was to develop a large twin-engine transport that could beat the fuel consumption performance of a three-and four-engine aircraft. Boeing originally designed the 777 to be 6-8 percent more fuel efficient than the MD-11 and the A330/A340. [Dornheim, 1991] To accomplish this required the use of advanced materials, lightweight flight controls, and an improved aerodynamic design. For the first time on a Boeing commercial transport, some of the primary structure is made of lightweight composites. Specifically, the horizontal and vertical tail structural boxes are made of an advanced graphite epoxy material, and composites are used in the spoilers and flaps. Overall composite content is about nine percent by weight. Boeing also

used a new aluminum alloy for the upper wing skin which is a stronger refinement of materials used on the company's three most recent transports. Lower weight was also achieved using fly-by-wire flight controls, thereby eliminating the need for heavy hydraulics. The use of electronic flight controls, which have been used in military aircraft since the middle 1970's, was a first for a Boeing commercial transport. These approaches to keep weight down have been very effective, yet the 777 was expected to be several percent overweight. [O'Lone, 1991]

In addition to reducing weight, the 777 designers intended to achieve fuel consumption goals by improving aerodynamic efficiency. According to Boeing, the 777 wing is the most aerodynamically efficient airfoil ever developed for a subsonic commercial aircraft. [Boeing, ca 1994] The 777 development team also faced a major aerodynamic challenge of fitting the large engine nacelle onto the wing with the least drag penalty. To further reduce drag, Boeing designed parts of the airplane to exceptionally close tolerances for a tight fit. [Air & Space, 1994] By using the advanced supercomputer simulation tool of computational fluid dynamics (CFD) and extensive wind tunnel testing to validate the CFD models, the 777 designers were able to produce an overall design that met its aerodynamic performance goals.

The 777 team had another challenge developing the propulsion units. Since this large airplane is designed to fly with only two engines, each must be very large and powerful. In fact, the diameter of each of the three different candidate engines is about the same as the fuselage diameter of the 737. The three companies which each developed an engine for the 777 are Pratt & Whitney, General Electric, and Rolls Royce. Of these, only Pratt & Whitney offered a unit that was derived directly from an existing engine design, thereby avoiding considerable development. Despite being a derivative design, the Pratt & Whitney unit did experience problems during development testing. Resolving these problems has been crucial to Boeing, because sales of the 777s are dependent on special early Federal Aviation Administration (FAA) certification called extended twin-engine operations overwater (ETOPS). This certification allows twin engine aircraft to fly long distance flights over water. All prior twin engine passenger jets that fly intercontinental distances over oceans have required several years of overland experience to develop a reliability history to justify ETOPS certification. Without ETOPS certification at time of the first 777 deliveries, the aircraft cannot be used for many of the routes for which they are being purchased. ETOPS was granted before the first scheduled passenger flight.

Another key feature that posed challenges to designers was the highly integrated and automated advanced avionics, enabling

operation by a crew of only two pilots instead of a usual cockpit crew of three. The resulting Airplane Information Management System (AIMS) from Honeywell incorporates into a single system the flight management, airplane condition monitoring, central maintenance and digital link communication functions, which in earlier aircraft were performed separately. Despite the high degree of integration, the cockpit has been designed with the growth potential to accommodate future needs for additional information. [Scott, 1991]

Design flexibility has also been incorporated throughout the rest of the 777 so that it can meet a variety of customer requirements. For example, the initial version will carry up to 375 passengers a distance of over 4,560 miles (3,970 nautical miles). Boeing plans to evolve the design into configurations for carrying more than 300 passenger nearly 7,250 miles (6,300 nautical miles) and about 400 passengers over 7,000 miles. The floor was strengthened to accommodate the weight of future increases in passengers and flight amenities. Furthermore, zones of flexibility have been designed into the cabin areas as specified by the airlines. Within these zones, which have been pre-engineered to accommodate wiring, plumbing, and attachment fixtures, the galleys and lavatories can be positioned anywhere in one-inch increments. Furthermore, passenger service units and overhead stowage compartments are designed for quick removal without disturbing ceiling panels, air conditioning ducts, or

support structures. A typical 777 cabin configuration change is expected to take as little as 72 hours, while such a change might take two to three weeks on existing aircraft. [Boeing, ca 1994]

By any measure, the 777 is a large and complex system. It will have about 132,500 engineered, unique parts. By including rivets, bolts, and other fasteners in the count, the airplane will have more than three million. [Boeing, ca 1994] Boeing's job is to ensure that those many parts work together in a manner that will satisfy its customers. Customer satisfaction with the 777 cannot be directly measured yet since the first aircraft had just been delivered when this case study was completed. However, the approach with which Boeing developed the 777 suggests that the airline customers will be satisfied with what they receive.

**Systems Engineering Fundamentals**

Boeing is the world's largest developer and manufacturer of commercial passenger jet aircraft. Since the late 1950s, the company has developed the 707, 727, 737, 747, 757, and 767 series of passenger jets. Over those years, Boeing had developed and followed its version of a traditional approach to developing aircraft. That is, design engineers designing the aircraft separately and then giving the drawings and specifications to manufacturing for fabrication and to maintenance personnel for establishing maintenance procedures. This approach normally led

to significant changes as the manufacturing engineers discovered design inconsistencies and unproducible component configurations. It also resulted in higher life cycle costs, since the designs did not always emphasize ease of repair and reduced need for maintenance. With the 777, Boeing decided on a radically new development approach that focused on the customer and placed great emphasis on ensuring that the development activities were done right the first time.

In late 1986, Boeing started identifying requirements for a large passenger airplane with the capacity between the twin-engine 767-300 and the four-engine 747-400 jumbo jet. This investigation into what Boeing then called the 767-X configuration was initiated as a result of interest expressed by airlines for a medium- to long-distance Boeing-produced aircraft in the 300-400 passenger capacity range. Boeing entered into a dialogue with interested airlines and potential subcontractors to define and refine requirements. Trade studies were conducted throughout this time, culminating in a system design concept with detailed requirements allocated to lower level elements of the aircraft. By the end of this period, a group of national and international subcontractors were ready to develop and fabricate many of the subsystems. This four-year requirements generation, requirements validation, concept development, and make-or-buy decision effort culminated with the launching of FSED.

Boeing's development and systems engineering approach is highlighted by early participation of all disciplines as well as by unprecedented input by customer airlines. The basic organizational entity responsible for designing and building a portion of the aircraft is the design/build team, with its membership comprised of design engineering, manufacturing, specialty engineering, and non-technical representatives, as well as representatives of the subcontractors and suppliers. The objective of the approach is to cut development costs by reducing the amount of downstream design changes and resultant rework, the predominant aircraft development cost drivers. [O'Lone, 1991]

On the 777 program, the teams have been organized around parts of the aircraft rather than functions. At the top are thirty integration-level teams representing the largest aircraft sections, and each has had the responsibility to maintain the interfaces of its component parts to the other twenty-nine sections. Various levels of subsystem and component sub-teams operate below. During the height of development, up to 238 of these cross-functional design/build teams worked on the effort at one time. [Boeing, 1994]

Subcontractors and suppliers have had unusually close working relationships with Boeing under this structure. [O'Lone, 1991] For example, in cases where the subcontractor was going to build the hardware, that company's representative took the lead

manufacturing role on the design/build team instead of a Boeing employee. The airline companies that placed the first orders have also taken part in the design/build process by participating in integration-level design/build meetings, preliminary design reviews, and critical design reviews. This continual involvement by the customers and their active involvement in defining the design helped to validate the requirements that the airlines had established before the program started.

A crucial element of Boeing's development strategy was designing the 777 on an advanced computer aided design (CAD) system instead of using paper drawings. This tool, called CATIA, is a three-dimensional computer system with solid modeling capability that can produce a virtual prototype. That is, the parts can be separately drawn in three dimensions, joined together in the computer, and visually displayed on the screen. This enabled each team to create their designs and compare them with the other teams' work to check for interference between parts. With over 2,000 computer terminals linked together and available to the development team, CATIA improved the speed of determining and communicating the status of interfaces and configurations, and it greatly increased the effectiveness of configuration control activities.

Engineers have also been able to use CATIA to analyze weights, balance, and stress on the different parts, allowing for quick

evaluation and refinement of alternative designs. This virtual prototyping not only eliminated the need for most paper drawings, but also the need for and cost of most physical mockups and full-scale prototypes. The most significant example is that the first 777 produced and flown was a production configuration aircraft instead of an engineering prototype.

In addition to design, analysis, and verification activities, the CATIA digital design system has had a large impact on manufacturing operations as well. CATIA design information was combined with computer controlled machining techniques, and it has resulted in a significant improvement in dimensional accuracy. [O'Lone, 1992] CATIA has also effected the replacement of plaster master models with digital data, greatly improving the precision and efficiency in building manufacturing tools. Additionally, Boeing has implemented a paperless manufacturing floor where the assembly and installation shop floor control system is computer based and enhanced by graphical instructions with links to the CATIA design database. Due to the digital design and manufacturing system, Boeing reports a 50 percent reduction of rework and factory floor changes compared to the 767. [Proctor, 1993]

Boeing planned a 54 month development schedule, which is somewhat greater than its traditional 48 months for a new commercial aircraft. [O'Lone, 1989] This was to allow more time for Boeing

to work out problems before aircraft delivery. In essence, Boeing is taking the aircraft through a break-in period to identify and correct annoying problems instead of having the airlines experience them. This "service-ready" approach was the guiding philosophy of the development program, and it drove the Boeing team to interact closely with the customer during development, to conduct extensive integrated ground testing, to perform additional flight testing, and to address life cycle supportability issues early. This approach was motivated by the significant difficulties experienced by airlines when they received the initial deliveries of the 747-400 in 1989.

As mentioned above, one of the strategies for achieving the service ready goals has been extensive integrated ground testing. This has been a key element in identifying and solving development problems as early as possible in order to attain reliability goals. Boeing invested $370 million in a new test facility called the Integrated Aircraft Systems Laboratory (IASL) to accomplish this. The IASL tests individual parts, subassemblies, and integrated aircraft systems both on the static bench and under simulated flight conditions. During advanced testing, multiple hardware systems are integrated and operated "in-the-loop" with the computer simulations. In addition to ground testing of subsystems, Boeing demonstrated the performance of its fly-by-wire design and cockpit avionics on its flying avionics testbed, a modified 757, prior to the first 777 flight.

Extensive flight testing was another strategy being used to achieve "service ready" goals. Using nine 777 aircraft, Boeing accumulated about twice as much flight test time before delivering the first aircraft to customers as it normally would. [Dornheim, 1994] While Boeing has had to conduct extensive flight testing to certify performance of the 777, about 60 percent of the overall test time was aimed solely at meeting service ready goals and is not required for FAA certification. [Dornheim, 1994]

Placing high emphasis on life cycle considerations early in development was another important Boeing strategy. Much of the input into design decisions affecting supportability issues came from the airlines. Most of these changes focused on improving aircraft reliability and maintainability. Specifically, lowering maintenance costs was a design goal, because maintenance labor expenses consume up to 35 percent of revenues at some airlines. [Proctor, 1994b] An example of development team supportability emphasis is the Onboard Maintenance System (OMS). The OMS operates as part of the AIMS discussed earlier, and it automatically records data of interest to maintenance personnel at the aircraft's destination, thereby reducing the time to determine corrective actions. Another example is that shop maintenance personnel from four airlines evaluated proposed procedures for speed and degree of difficulty as soon as draft versions were issued. The result is that final maintenance

manuals were ready for the fourth flight test aircraft instead of after initial customer deliveries as is the norm for Boeing aircraft. Also, due to the close coordination between Boeing and the airline maintenance department, United Airlines will for the first time directly use Boeing maintenance manuals instead of redeveloping them first. [Proctor, 1994a]

Another Boeing supportability objective was to have pilot training simulators in operation prior to delivery of the first aircraft. CAE Electronics Inc. worked closely with Boeing to develop 777 flight simulators in parallel with the aircraft, and a partial simulator was available to support training for the first flight.

As a result of the maintenance improvements as well as the fuel efficiency advances, Boeing estimates that the 777 will cost 10 percent less to operate than the four engine A340 and about 8 percent less than the three engine MD-11. [Holusha, 1991]

To keep track of the many different issues, activities, participants, and costs being addressed by a large team, Boeing implemented a strong program management system to collect the cost and technical progress data and information from the design/build groups and provide it to the managers for evaluation. The organizational structure of Boeing's concurrent engineering development approach and the communication tools

available produced an environment by which the effort could be effectively tracked and managed.

**Development Environment**

Boeing's concurrent engineering approach helped foster an environment conducive to appropriate and successful systems engineering practices. A prime feature has been emphasis on the customer. Boeing gave actual and potential customers major voices in the development of the 777. Airlines had early and continuous involvement in the design process, and it has resulted in significant operational improvements that have increased the aircraft's appeal to them. [Aviation Week, 1994] Through initial market surveys, Boeing learned the airline's basic desires. Many of the airlines wanted a large transport that uses an engine whose design is essentially a modified version, or derivative, of an already existing engine in use, not a totally new one. Boeing complied by giving the airlines the choice of a derivative engine from Pratt & Whitney and two new engines from General Electric and Rolls-Royce.

It was through full-time, on-site airline advisory teams at Boeing, though, that the initial airline customers, United, All Nippons Airways, British Airways, and Cathay Pacific, had influence over lower-level design details. Their representatives were involved in reviewing the design and developing flight and

maintenance procedures. Based on airline advisory team inputs, Boeing developed a new technology cockpit derived from the advanced 747-400 cockpit instead of the 767 as it was planning. Airlines also played a pivotal role in determining the width of the fuselage. An airline representative also suggested the folding wingtips option as a solution to airport gate compatibility problems resulting from the wide wingspan. While the customers influenced some detailed design decisions, the fundamental requirements remained stable throughout development.

In addition to steadfast requirements, funding and workforce levels followed a stable, long-term plan. The Boeing Company had totally committed itself to the four and a half year development program, and that included corporate funding to accomplish it. While Boeing was not at the mercy of its 777 customers for immediate operating funds, it did attempt to secure as many orders as possible as early as possible in hopes of recouping development costs as quickly as possible. In fact, the program was initiated with firm orders from United Airlines for 34 aircraft and options for 34 more, part of the largest single commercial order in Boeing's history. [O'Lone, 1990]

While the 777 development team was large, most key designers and managers remained throughout the development. This included not only Boeing employees, but also the major subcontractors. Boeing's development approach depended partly on establishing

close, long-term relationships with subcontractors and suppliers so as to ensure the availability of dependable sources into production. This relationship building was also helpful in fostering cooperation among all team members. The team spirit encouraged by Boeing and the creation of multi-disciplinary, multi-company teams promoted cooperation among all stakeholders.

Cooperation among all the program participants was further enhanced by the means of communication and coordination provided by Boeing. As previously discussed, CATIA gave nearly everyone in the design process instant access to the same configuration and status information. In addition, subcontractors and vendors had real-time access to select portions of the data base. With all teams and the thousands of team members using the equivalent of the same set of the latest drawings at any given time, CATIA has been serving as a communication tool that promotes the concurrent engineering approach. While the 777 is not the first aircraft development effort adopting a "paperless" design approach, it is the first commercial aircraft program to adopt such a practice as completely as it has.

Communication was also enhanced by locating the entire Boeing 777 development team in the same general area in and around Seattle, Washington. Also residing in the Boeing program offices were full-time, on-site representatives from the major subcontractors and initial airline customers.

The advanced communication environment would have had minimal impact unless the workers knew what their responsibilities were. In Boeing's design/build team structure, every worker had the means to clearly understand his or her responsibilities because each team had a written charter defining them. Furthermore, Boeing defined the relationships between the different levels of teams in an official document before the start of FSED. This document, a cross between a program management plan and a systems engineering management plan, has had to be updated to reflect the continually changing list of design/build teams.

While Boeing is a large corporation, and the 777 development team consists of thousands of people, Boeing provided the design/build teams with the authority and autonomy to carry out their responsibilities without major interference from corporate headquarters. Furthermore, because of the speed of CATIA and its wide access, design changes were processed, evaluated, and implemented quickly, thereby contributing to an environment allowing a fairly high degree of design flexibility.

This level of flexibility and autonomy was also made possible by the expertise and experience of the workforce. Boeing has been designing and producing passenger jets for over 30 years, and the technical knowledge gained during that time has been resident in the team since the 777's inception. Furthermore, Boeing employed many workers with experience gained in the 747-400 development

conducted in the mid- to late-1980s. In addition, many of the key subcontractors are specialists at developing particular items, and they also have long histories of successful aerospace products lines. The 777 development team can therefore be viewed as being highly capable.

Since profitability of the 777 program is dependent on the number of aircraft produced, Boeing would like to sell as many as possible. Future sales, however, are highly dependent on how well the initial aircraft perform in service. While Boeing's reputation for developing good passenger aircraft helped it gain initial customers, the company is accountable for the performance of the 777. In order to ensure that its customers are provided with the performance they ordered, Boeing warranties key performance parameters and workmanship.

**Summary/Conclusion**

The 777 represents a new approach to designing and building aircraft by Boeing. It was made possible by a new development philosophy, new computer-based design and information technology, and a new cooperative attitude on the part of the company integrated with the recognized practices and tools of aerospace design. The start of flight testing on schedule, the high degree of customer involvement throughout all phases of development, and delivery of the first production unit on-time suggest a design

with a significant potential for success throughout its service life.

Table 3.1-1 777 Performance scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| TECHNICAL PERFORMANCE - INITIAL | 0-10 | 1 | 8 | 8 |
| TECHNICAL PERFORMANCE - MATURE | 0-10 | 1 | 10 | 10 |
| COST PERFORMANCE | 0-10 | 1 | 8 | 8 |
| SCHEDULE PERFORMANCE | 0-10 | 1 | 10 | 10 |
| PERFORMANCE TOTAL | | | | 36 |

Table 3.1-2 777 Systems Engineering Fundamentals scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| REQUIREMENTS DEVELOPMENT | 0-10 | 2 | 10 | 20 |
| INCIPIENT SYSTEM DESIGN | 0-10 | 2 | 9 | 18 |
| EVALUATING ALTERNATIVE CONCEPTS AND DESIGNS | 0-10 | 1 | 10 | 10 |
| MAKE-OR-BUY DECISION | 0-10 | 1 | 10 | 10 |
| VALIDATION | 0-10 | 1 | 9 | 9 |
| VERIFICATION AND INTEGRATED TESTING | 0-10 | 1 | 10 | 10 |
| CONFIGURATION MANAGEMENT | 0-10 | 1 | 10 | 10 |
| MANUFACTURING CONSIDERATIONS | 0-10 | 1 | 9 | 9 |
| SYSTEMS INTEGRATION AND TECHNICAL MANAGEMENT | 0-10 | 1 | 10 | 10 |
| LIFE CYCLE CONSIDERATIONS | 0-10 | 1 | 10 | 10 |
| PROGRAM MANAGEMENT | 0-10 | 1 | 10 | 10 |
| SYSTEMS ENGINEERING FUNDAMENTALS TOTAL | | | | 126 |

Table 3.1-3 777 Development Environment scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| EMPHASIS ON THE CUSTOMER | 0-10 | 1 | 10 | 10 |
| STABILITY OF REQUIREMENTS AND CONFIGURATION | 0-10 | 1 | 8 | 8 |
| FUNDING AND WORKFORCE-LEVEL STABILITY | 0-10 | 1 | 9 | 9 |
| STRONG SUPPORT FOR PROGRAM | 0-10 | 1 | 10 | 10 |
| CONTINUITY OF CORE DEVELOPMENT TEAM | 0-10 | 1 | 9 | 9 |
| STABILITY OF ORGANIZATIONAL STRUCTURE | 0-10 | 1 | 9 | 9 |
| COOPERATION AMONG ALL STAKEHOLDERS | 0-10 | 1 | 9 | 9 |
| EFFECTIVE COMMUNICATION WITHIN TEAM | 0-10 | 1 | 9 | 9 |
| FLEXIBILITY AND AUTONOMY | 0-10 | 1 | 7 | 7 |
| WORKFORCE EXPERTISE AND EXPERIENCE | 0-10 | 1 | 8 | 8 |
| ACCOUNTABILITY FOR SYSTEM PERFORMANCE | 0-10 | 1 | 8 | 8 |
| DEVELOPMENT ENVIRONMENT TOTAL | | | | 96 |

Table 3.1-4 777 Design Difficulty scores.

| Elements | Range | Score |
|---|---|---|
| TYPE | 0-15 | 9 |
| KNOWLEDGE COMPLEXITY | 0-10 | 6 |
| STEPS | 0-10 | 9 |
| QUALITY IMPLEMENTATION EFFORT | 0-10 | 9 |
| MANUFACTURING OPERATIONS IMPLEMENTATION EFFORT | 0-5 | 4 |
| SELLING PRICE CONSTRAINT | 0-5 | 4 |
| DESIGN DIFFICULTY TOTAL | 0-55 | 41 |

Table 3.1-5 777 Resources scores.

| Elements | Range | Score |
|---|---|---|
| COST | 0-15 | 12 |
| TIME | 0-10 | 7 |
| INFRASTRUCTURE | 0-10 | 8 |
| RESOURCES TOTAL | 0-35 | 27 |

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## 3.2 CASE STUDY: LOCKHEED F-117 STEALTH FIGHTER

The F-117 Stealth Fighter is a transonic, single-pilot Air Force jet developed by Lockheed with the primary mission of penetrating enemy airspace at night undetected, destroying specifically designated high value targets, and surviving. [Miller, 1993] The design of the F-117 takes advantage of low observability technology, rendering the aircraft nearly invisible to radars and other detection sensors. The F-117 represents a revolution in aircraft design, and it is the first aircraft in which low observability, or stealthiness, was the main design objective. [Goff, ca 1992] While the Stealth Fighter employed breakthrough technology, the development risk was minimized by the use of existing subsystems and technologies throughout the rest of the aircraft. Furthermore, it was developed in an environment conducive to generating innovative designs.

### Development History, Design, and Performance

What eventually became the F-117 program began as a low-level investigation sponsored by the Defense Advanced Research Projects Agency (DARPA) into stealth technologies in 1974. DARPA had requested that several aircraft manufacturers conduct competitive preliminary studies addressing a fighter with significantly reduced radar detectability. Technologies to counter radar detection and tracking had been investigated to a limited degree

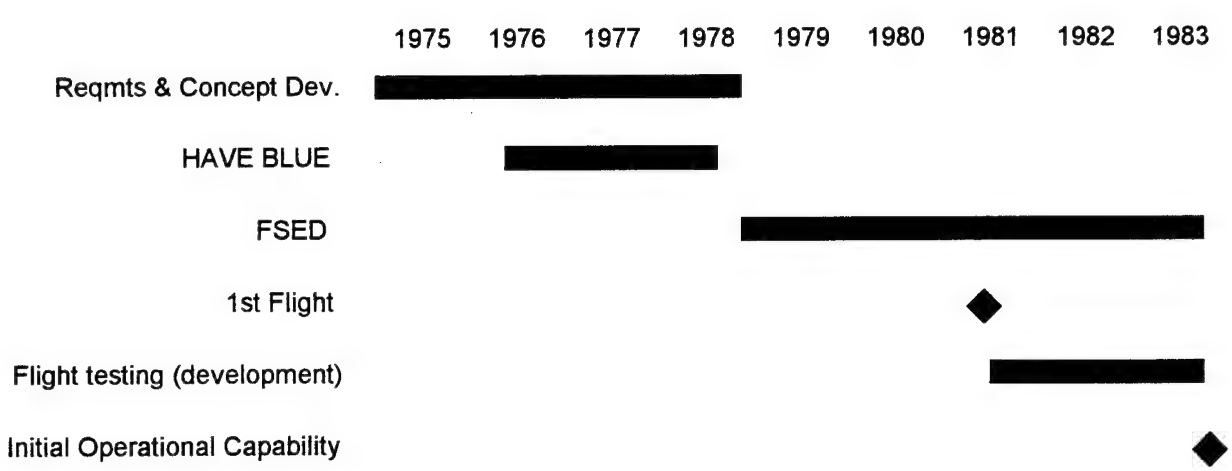
since the mid-1950's. For example, the reduction of radar cross section was a goal of the Lockheed A-12 and SR-71 development. However, it was not until the Vietnam War and the threat of radar guided surface-to-air missiles that a compelling need was recognized by military planners.

After the studies were completed, two of the contractors were invited to participate in a competitive effort to develop and test a stealth aircraft. The team from one of the two contractors, Lockheed, created a revolutionary stealth design computer code and performed static low observability model demonstrations supporting the results of the code. Based on these achievements, Lockheed won the competition in April 1976 to design, develop, and test two advanced technology prototypes for flight testing in an 18 month classified advanced technology development program called Have Blue.

The program called for a variety of tests, including radar cross section and wind tunnel model tests of the prototype design, qualification and proof tests for various systems and subsystems, preflight testing of the assembled aircraft, and flight testing. The first flight of the unorthodox looking Have Blue prototype was December 1, 1977, 20 months after contract award. The second prototype incorporating modifications over the first was delivered seven months later, and flight testing continued until the summer of 1978.

Based on the results of the prototype flight tests, the Air Force awarded a fixed-price full-scale engineering development (FSED) contract and fixed-price production contract under the program name SENIOR TREND to Lockheed in November 1978 and December 1979 respectively for concurrent development and production of five FSED prototypes and 15 production units based on the HAVE BLUE prototype design. The first F-117 flight occurred on 18 June 1981, 31 months after start of FSED, and it became operational in October 1983, a total of 60 months from FSED start. (See Figure 3.2.) The schedule for first flight and initial operational capability by the Air Force was about a year late (about 25 percent), due to the crashes of two F-117s and specific development problems. The Air Force eventually bought a total of 59 F-117s, which were produced at a rate of about eight per year, with the final unit was delivered in July 1990. The entire program was classified and conducted in secret until it was acknowledged to the public in November 1988.

Figure 3.2 F-117 development schedule



The total cost of the Stealth Fighter development for 1978-1990 in then-year dollars was about $6.27 billion. This represents $2 billion for development and $4.27 billion for producing 59 aircraft. Over the life of the development program, FSED costs increased by 53 percent, according to Air Force testimony to a U.S. senate subcommittee. A significant amount of this was due to inflation and to delays stemming from the crashes of two F-117s. [Lynch, 1992]

The revolutionary nature of stealth technology requirements ensured that there would be a variety of developmental challenges. The major one was to develop a stealthy but flyable and maneuverable external configuration in which to integrate the aircraft subsystems. The design also had to meet minimum range and speed requirements. In all, the F-117 designers had to address seven types of observable signatures that can be used to detect an aircraft: radar, infrared, visual, contrails, engine smoke, acoustic, and electromagnetic radiation. Having to deal with all these issues significantly increased aerodynamic and subsystem integration difficulties.

Lockheed's approach to moving stealth from concept to reality was to rely on off-the-shelf hardware when possible, modify existing equipment where feasible, and invent new systems only when required. [Miller, 1993] The objectives were to minimize system development risks and costs, enabling the design engineers to

focus on the breakthrough of reducing radar cross section without having to invent new avionics and engines. [Miller, 1993] To accomplish this, subsystems and components were taken from a wide variety of aircraft existing at the time. For example, most of the cockpit avionics and the engines were derived from the McDonnell Douglas F/A-18 fighter, flight controls came from the General Dynamics F-16 fighter, the landing gear and ejection seat were from the McDonnell Douglas F-15 fighter, the inertial navigation system was adapted from the Boeing B-52 bomber, and the environmental control system components came from the Lockheed C-130 transport. Other subsystems and components were obtained from many other airplanes going as far back as the T-33 jet trainer of the early 1950s.

While appropriate subsystems were readily available, answers to ensure stealthiness of design were not. According to Lockheed officials, one of the most difficult issues to solve involved the four small pitot tubes that extend from the aircraft nose to gather air data. [Hughes, 1991] The presence of these four small items had a significant impact on the size of the radar signature. It took engineers three years to come up with a design solution to preserve the F-117's low observability with the pitot tubes.

Aircraft shape, though, was just one consideration of low observability. The Lockheed designers developed radar absorbent

material (RAM) coatings used over the primarily aluminum structure and used special composite materials as weapons bay and landing gear doors, thereby reducing the aircraft's reflectivity of radar. Another challenge was to hide the hot exhaust of the engines from infrared and visual detection. This was accomplished by developing a tailpipe that would flatten and cool the exhaust while simultaneously shrouding radar-reflecting portions of the plane. A variety of other design features were also added throughout development to enhance low observability performance.

The result of emphasizing stealthiness over aerodynamics made the F-117 unstable in flight. This dictated that the flight control system had to be a full-time, computer controlled, fly-by-wire command augmentation system. [Miller, 1993] The only technology with adequate technical maturity at the time was the control system used on the then newly operational General Dynamics F-16. The only significant change required was to develop new control laws, and they were flight tested in a specially modified T-33 jet before the first F-117 flight.

Despite the use of mostly off-the-shelf avionics, integrating them was a major challenge made more difficult by the stealth requirements which mandated substantial integration of airframe/avionics design. An example of an important item with integration difficulties was the Texas Instruments Infrared Acquisition and Detection System (IRADS), the laser targeting

subsystem for the F-117's two 2,000 pound precision guided bombs. Making the turret openings of this crucial subsystem invisible to radar was a major problem. The difficulty was finding a material for the turret coverings that would allow the laser and infrared emissions to penetrate freely while remaining invisible to enemy radar. After trying several high priced transparent materials, the eventual solution was an innovative use of inexpensive fine wire mesh covering the opening.

As a military aircraft, the F-117, in addition to stealth design and weapons, required other special features not seen on commercial aircraft. Primary among these were an ejection seat, defensive avionics, and aerial refueling capability.

The five FSED aircraft incorporating all the design features were involved in F-117 flight testing, and they were modified throughout development to test design refinements. Flight testing was crucial to the design process, especially considering the limited simulation tools available to investigate stealth issues. The results of flight testing of the first five aircraft contributed to design changes that would be implemented as the succeeding production aircraft were being fabricated. Some of the initial off-the-shelf subsystems used to reduce development risk were found to be inadequate in flight testing and had to be modified or replaced.

The F-117 flight test program encountered some significant problems in determining the adequacy of design solutions and the resolution of design problems. The difficulties stemmed from the fact that six different test pilots were flying three different airplanes during initial phases of flight testing. What was adequate performance for one pilot was in some cases inadequate for another. Furthermore, each test aircraft demonstrated its "own personality due to equipment installation tolerances." [Lynch, 1992] Consequently, flight testing got into trouble when Lockheed tried to solve too many problems at the same time. In one case, the problem was solved by designating a single aircraft and pilot to perform the particular tests. [Lynch, 1993]

A considerable series of ground testing of the test aircraft was performed prior to the first flight and continued throughout FSED. In addition to wind tunnel and radar cross section testing, extensive component, subsystem, and integration testing of avionics was accomplished. Also, the essential testing to certify initial proficiency of the aircraft, somewhat equivalent to certification by the Federal Aviation Administration, was completed by the initial operational capability date of October 1983. However, flight testing continued on for several years to accomplish objectives that would not fit in the Air Force's original schedule. [Lynch, 1992]

The number of F-117s planned for fabrication was small, rendering the development of advanced manufacturing and assembly processes and procedures financially impractical. Consequently, much of the F-117 fabrication and assembly was done by hand. The quality appears to have been very good, with one significant exception. The first production unit crashed because the airplane's roll-rate and pitch rate gyroscopes had been crossed when they were installed. This was an example of inadequate inspection, ground testing, and possibly deficient attention to development of manufacturing and assembly instructions. However, it does not appear to have been evident throughout development.

The Air Force has been satisfied with F-117 performance; the aircraft achieved the stealth, range, and speed requirements set at the beginning of the program. While the aircraft was developed with limited performance objectives, its design has proved to be somewhat robust. For example, in Desert Storm, the F-117 was used very successfully in a manner significantly different than its original purpose: performing a few specialized missions. In the Middle East, the F-117s were flying one or two operational missions per night during much of the air campaign. [Kandebo, 1992] While robust in one sense, such prolonged operations resulted in increased maintenance costs.

The Air Force and Lockheed continued to modify and upgrade the F-117 throughout its production and operational deployment to

enhance the F-117's capability and enable the aircraft to take on new roles. The original flight computer, for example, was replaced in 1984 with a repackaged version of the Space Shuttle computer in order to upgrade marginal capability. Later, new avionics were installed, and the engine exhaust system was modified. Some new communications equipment gave the F-117 all-weather mission capabilities. The changes have been made to enhance the F-117 operability, maintainability and to minimize support costs, not to correct shortcomings to initial requirements. [Hughes, 1991]

**Systems Engineering Fundamentals**

The F-117 development is characterized by the successful accomplishment of many of the fundamental systems engineering practices. Requirements definition was one of them. The written requirements placed on contract at the beginning of FSED were the result of a series of requirements and technology studies and the advanced prototype Have Blue development. Throughout this period, the Air Force refined what it operationally required based on enemy capabilities. Furthermore, the program was technology driven, and mostly critical performance and safety parameters were specified as requirements.

The Lockheed development team defined system and subsystem models and allocated requirements. Functional requirements were defined

and work broken out according to a detailed work breakdown structure. The team also made use of a variety of design and analysis models and simulations of somewhat limited capabilities in order to evaluate and decide among alternative concepts and subsystem designs. The F-117 was developed with the design tools available to the aeronautics community in the mid- to late-1970s. High and low speed wind tunnels, low performance computers for running simple simulations and analysis programs, and calculators. The design team had no supercomputers, and much of the initial design calculations were done by hand.

Despite their limitations, a variety of computer simulations and physical models were essential to development. One computer program in particular, ECHO 1, guided the stealth shape design during Have Blue and the FSED program. ECHO 1 allowed aircraft designers to predict a radar return. This early computer modeling tool, however, was limited to calculations in only two dimensions. This meant that the resulting aircraft would have a faceted design rather than a smooth, seamless one. [Kandebo] Lockheed tested their calculations with a one-third scale model for radar cross section studies, giving credence to computer simulation outputs.

As discussed previously, prototyping played a major role in F-117 development. The two advanced technology prototypes produced during the Have Blue program were 40 percent smaller than the

eventual production aircraft and simpler. However, they were successful in their role of testing certain performance projections that had been based on unvalidated models.

Physical modeling also played a role in production. Lockheed constructed a full-scale wooden mockup in 1979 before assembly line activities commenced. This was done so the exact shape and fit of each critical facet panel and component could be defined.

Another indicator of successful systems engineering practices was the definition of the integrated testing approach early in the development process. The series of integrated avionics and stealth tests on the ground, flight control testing on other aircraft, and flight testing requirements were well documented prior to start of FSED.

The Lockheed team kept tight control over the F-117 drawings and specifications defining the configuration, including the internal and external interfaces. A simple yet flexible drawing and configuration change system was in place that allowed fast turnaround of changes resulting from testing and other verification activities.

To integrate the widely varied and interdependent work carried on by relatively small groups of Lockheed employees and that of about 500 subcontractors and suppliers, a strong systems

integration and technical management presence was provided by the Lockheed program manager and his deputies. They kept the focus on the requirements and succeeded in integrating the subsystems into the stealth shell.

While the F-117 was a complex system to design and fabricate, its development focus was somewhat narrow and carried out at the expense of other considerations. With this in mind, supportability, discussed here primarily in terms of maintainability, was considered in the design process of the F-117 but was not a driving requirement. Like other performance considerations, it took a back seat to stealth. Where stealth performance was very good, critics contend the F-117 is a prime example of what happens when support issues receive low priority. [Aviation Week, 1990] Case in point: The F-117 presents a problem for technicians because stealth minimizes the number of access panels and openings in the skin in order to obtain the smallest radar cross section possible. The restricted access makes the aircraft more difficult, time consuming, and expensive to work on. Maintainability considerations, however, did have an impact on this matter. Because of feedback resulting from evaluation of the first F-117 by Air Force maintenance specialists, more panels and doors were added on subsequent units to lessen the accessibility problems. [Henderson, 1991] In another recognition of supportability considerations, Lockheed simplified the necessary maintenance and reduced the frequency

with which RAM coatings would need to be removed.

With the exception of coating maintenance, the F-117 maintenance practices are similar to those used for F-15s and F-16s. This is due largely to the fact that most of the subsystems came from existing operational aircraft. As a consequence, more than 95 percent of the equipment used to support the F-117 is common to that of other Air Force aircraft. [Aviation Week, 1990] Furthermore, despite the unique requirement of coating maintenance and minimal access panels, the Air Force claims the F-117 maintenance costs during normal operations are comparable to those of other tactical aircraft. [Aviation Week, 1990]

While the emphasis on supportability was limited, the Air Force included only limited supportability requirements. Had the Air Force levied strict requirements, the F-117 may not look the same or have been successfully developed at all. This was a major tradeoff the Air Force customer was willing to make to achieve a revolutionary breakthrough in performance.

With regards to program management, Lockheed managers utilized sufficient scheduling, work, and cost tracking techniques throughout development to assess technical progress and maintain control.

**Development Environment**

The F-117 was developed in an environment that emphasized the Air Force customer. The F-117 contractor team followed the golden rule: he who has the gold, rules. Therefore, Lockheed was responsive to Air Force, and kept its representatives informed of all technical developments. Furthermore, the F-117 contractor team reviewed the design progress with the Air Force customer at a series of major requirements and design reviews, and Air Force pilots, weapons, and maintenance crews were heavily involved during FSED.

The F-117 was also developed in a stable, protected environment that supported innovative solutions. Due to its revolutionary military nature, the effort had strong government support at the highest levels and was carried out in complete secrecy without micromanagement from Congress or the Air Force. Additionally, funding from the Air Force was stable. Furthermore, working relationships between the Air Force customer and the contractor development personnel were non-adversarial, and they operated together in a problem-solving atmosphere. [Miller, 1993] These various factors were essential in enabling the program to follow very tight schedules. The classification of the program, however, did cause problems in hiring people since extensive and lengthy security clearance checks had to be done on anyone coming into the program.

The F-117 design team was afforded the flexibility by the Air Force to carry out much of the design process as it saw appropriate. In addition to being free from many bureaucratic considerations, the aircraft was not overly specified, enabling the development team considerable flexibility in achieving the stealth performance. In case performance had not been met, Lockheed's contract with the Air Force included warranties covering the aircraft's required range, weapon delivery accuracy, radar cross section, and workmanship defects.

In addition to the items discussed above, stability of customer requirements, continuity of core team membership, ease of team communication and coordination, and a high level of workforce expertise and experience were all hallmarks of the F-117 development environment at Lockheed.

The F-117 was developed in Lockheed's Advanced Development Projects group called the "Skunk Works." The Skunk Works, which years earlier had developed the U-2, F-104, and the SR-71, was organized for the F-117 development as a tightly knit team of highly talented, innovative and motivated engineers and technicians. These included technically competent managers who were able to communicate effectively with the team and coordinate activities, enabling them to resolve design conflicts in a timely manner. This environment was conducive to generating technological breakthrough designs and then carrying those

designs through small-scale production. It is nearly a paragon environment for fast prototyping of advanced aircraft designs. Most of the development environment characteristics that support effective systems engineering practices are part of the Skunk Works mode of operation.

The Skunk Works approach is encapsulated in fourteen points or "rules" developed by its founder, Clarence "Kelly" Johnson. These principles can be viewed as addressing the systems engineering philosophy and practices of the F-117 development. Some of the key aspects of this streamlined approach are as follows [Miller, 1993]:

1) The program manager must have complete control of the program in all aspects. It is essential that the program manager have authority to make decisions quickly regarding technical, finance, schedule, or operational matters.
2) Strong but small project offices must be provided both by the customer and the contractor. The customer program manager must have similar authority to that of the contractor.
3) The number of people having any connection with the project must be severely restricted. This is because more people add bureaucracy, and bureaucracy makes unnecessary work.
4) A simple drawing and drawing release system with great flexibility for making changes must be provided. This permits early work by manufacturing organizations, and

schedule recovery if technical risks involve failures.

5) The number of required reports should be minimized, but important work must be recorded thoroughly. Responsible management does not require massive technical and information systems.

6) There must be a monthly cost review covering not only what has been spent and committed, but also projected costs to the conclusion of the program. Responsible management operates within the resources available.

7) The contractor must be delegated and must assume more than normal responsibility for obtaining good vendor bids for the subcontracts on the project. Commercial bid procedures are often better than military ones. The contractor must have the essential freedom to use the best talent available but also operate within the resources provided.

8) Responsibility for basic inspection should be given to subcontractors and vendors. The contractor should not be duplicating inspection.

9) The contractor must be delegated the authority to test the final product in flight, especially in the initial stages of development. This is critical if new technology and the attendant risks are to be rationally managed.

10) The specification applying to the hardware must be defined and finalized in advance of contracting. Furthermore, the Skunk Works practice of having a specification section stating clearly which military specification items will not

be complied with and the reasons for not doing so is highly recommended. Standard specifications inhibit new technology and innovation and are frequently obsolete.

11) Funding must be timely.

12) Mutual trust must exist between the customer project organization and the contractor, and there should be close cooperation and day-to-day communication. This cuts down misunderstanding and correspondence to a minimum. The goals of the customer and producer should be the same - get the job done well.

13) Access by outsiders to the project and its personnel must be strictly controlled by appropriate security measures.

14) Due to the small size of Skunk Works development teams, ways must be provided to financially reward people based on good performance and not on the number of people supervised. Responsible management must be rewarded, and responsible management does not permit the growth of bureaucracies.

The Lockheed team followed these tenets during development. Furthermore, the fact that the F-117 was a classified program facilitated the implementation of this systems engineering management approach.

**Summary/Conclusion**

The F-117 can be considered a successful design, and its development can be viewed as somewhat successful overall. Although the program experienced cost growth and schedule delays, the stealth fighter met the primary performance requirements demanded by the customer in the contract. The F-117 design was maximized for low observability while still meeting minimum range and speed requirements. The revolutionary design was also robust enough to enable its use at Desert Storm in a manner and at a frequency not originally anticipated. The conduct of this program in a stable, streamlined environment while strongly implementing the fundamentals of systems engineering was key to its technical performance success.

Table 3.2-1 F-117 Performance scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| TECHNICAL PERFORMANCE - INITIAL | 0-10 | 1 | 8 | 8 |
| TECHNICAL PERFORMANCE - MATURE | 0-10 | 1 | 10 | 10 |
| COST PERFORMANCE | 0-10 | 1 | 4 | 4 |
| SCHEDULE PERFORMANCE | 0-10 | 1 | 4 | 4 |
| PERFORMANCE TOTAL | | | | 26 |

Table 3.2-2 F-117 Systems Engineering Fundamentals scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| REQUIREMENTS DEVELOPMENT | 0-10 | 2 | 9 | 18 |
| INCIPIENT SYSTEM DESIGN | 0-10 | 2 | 9 | 18 |
| EVALUATING ALTERNATIVE CONCEPTS AND DESIGNS | 0-10 | 1 | 10 | 10 |
| MAKE-OR-BUY DECISION | 0-10 | 1 | 10 | 10 |
| VALIDATION | 0-10 | 1 | 9 | 9 |
| VERIFICATION AND INTEGRATED TESTING | 0-10 | 1 | 8 | 8 |
| CONFIGURATION MANAGEMENT | 0-10 | 1 | 9 | 9 |
| MANUFACTURING CONSIDERATIONS | 0-10 | 1 | 6 | 6 |
| SYSTEMS INTEGRATION AND TECHNICAL MANAGEMENT | 0-10 | 1 | 10 | 10 |
| LIFE CYCLE CONSIDERATIONS | 0-10 | 1 | 6 | 6 |
| PROGRAM MANAGEMENT | 0-10 | 1 | 9 | 9 |
| SYSTEMS ENGINEERING FUNDAMENTALS TOTAL | | | | 113 |

Table 3.2-3 F-117 Development Environment scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| EMPHASIS ON THE CUSTOMER | 0-10 | 1 | 9 | 9 |
| STABILITY OF REQUIREMENTS AND CONFIGURATION | 0-10 | 1 | 7 | 7 |
| FUNDING AND WORKFORCE-LEVEL STABILITY | 0-10 | 1 | 10 | 10 |
| STRONG SUPPORT FOR PROGRAM | 0-10 | 1 | 10 | 10 |
| CONTINUITY OF CORE DEVELOPMENT TEAM | 0-10 | 1 | 10 | 10 |
| STABILITY OF ORGANIZATIONAL STRUCTURE | 0-10 | 1 | 9 | 9 |
| COOPERATION AMONG ALL STAKEHOLDERS | 0-10 | 1 | 9 | 9 |
| EFFECTIVE COMMUNICATION WITHIN TEAM | 0-10 | 1 | 8 | 8 |
| FLEXIBILITY AND AUTONOMY | 0-10 | 1 | 8 | 8 |
| WORKFORCE EXPERTISE AND EXPERIENCE | 0-10 | 1 | 9 | 9 |
| ACCOUNTABILITY FOR SYSTEM PERFORMANCE | 0-10 | 1 | 8 | 8 |
| DEVELOPMENT ENVIRONMENT TOTAL | | | | 97 |

Table 3.2-4 F-117 Design Difficulty scores.

| Elements | Range | Score |
|---|---|---|
| TYPE | 0-15 | 13 |
| KNOWLEDGE COMPLEXITY | 0-10 | 8 |
| STEPS | 0-10 | 8 |
| QUALITY IMPLEMENTATION EFFORT | 0-10 | 7 |
| MANUFACTURING OPERATIONS IMPLEMENTATION EFFORT | 0-5 | 4 |
| SELLING PRICE CONSTRAINT | 0-5 | 1 |
| DESIGN DIFFICULTY TOTAL | 0-55 | 41 |

Table 3.2-5 F-117 Resources scores.

| Elements | Range | Score |
|---|---|---|
| COST | 0-15 | 9 |
| TIME | 0-10 | 7 |
| INFRASTRUCTURE | 0-10 | 8 |
| RESOURCES TOTAL | 0-35 | 24 |

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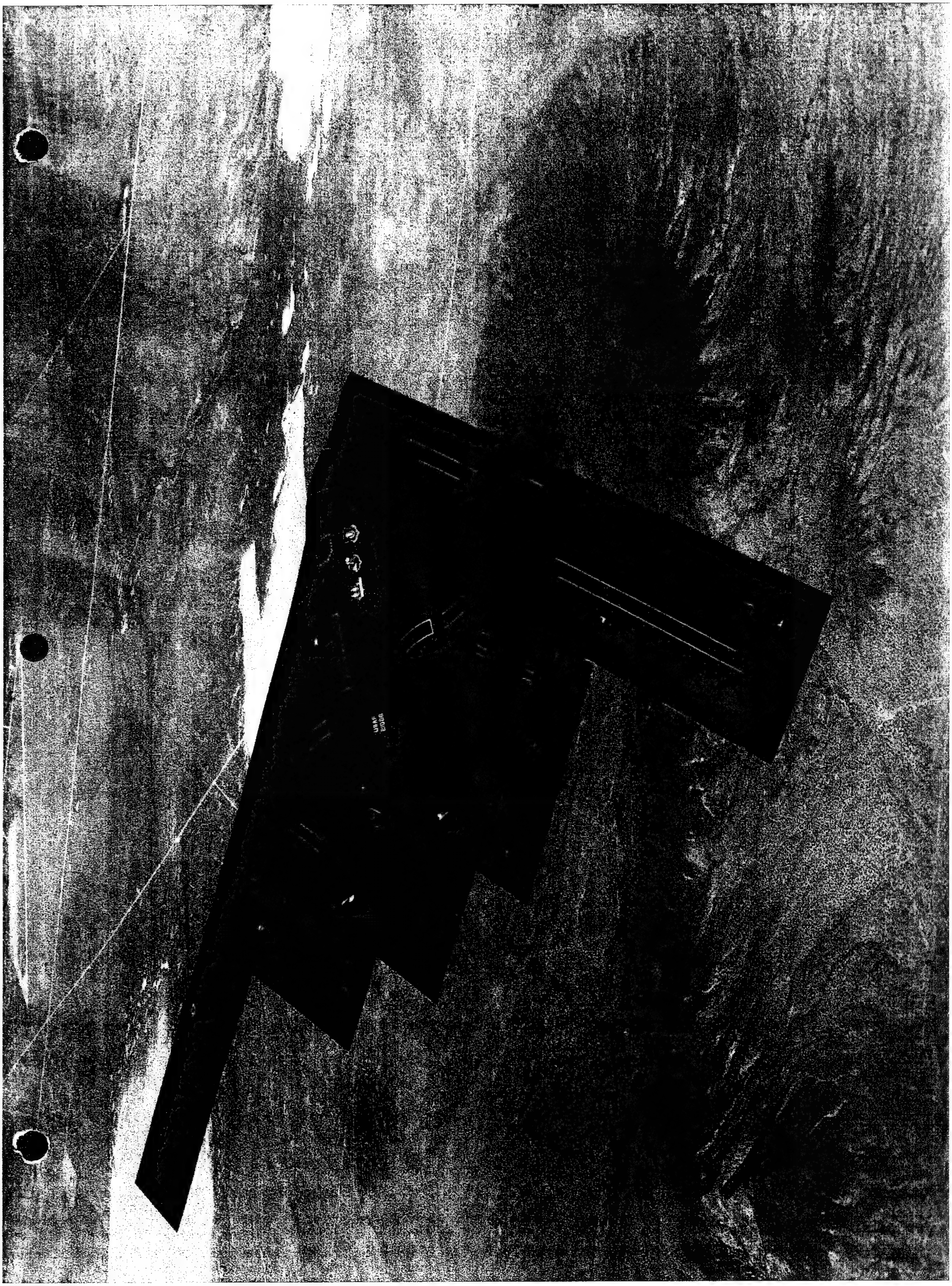


## 3.3 CASE STUDY: NORTHROP B-2 STEALTH BOMBER

The Northrop B-2 is the United States Air Force's newest intercontinental strategic bomber. This highly complex aircraft using revolutionary stealth technologies was designed to penetrate the air defenses of the former Soviet Union and survive in order to deliver nuclear weapons. With the end of the Cold War, the B-2 is expected to be capable of attacking heavily defended targets with precision guided conventional weapons in addition to its primary nuclear mission. The challenging and costly integration of this wing-shaped aircraft was made possible not only by breakthroughs in stealth technology, but also by new advanced manufacturing processes, a powerful computer tool for assisting in the design of large hardware systems, and the disciplined application of systems engineering principles.

### Development History, Design, and Performance

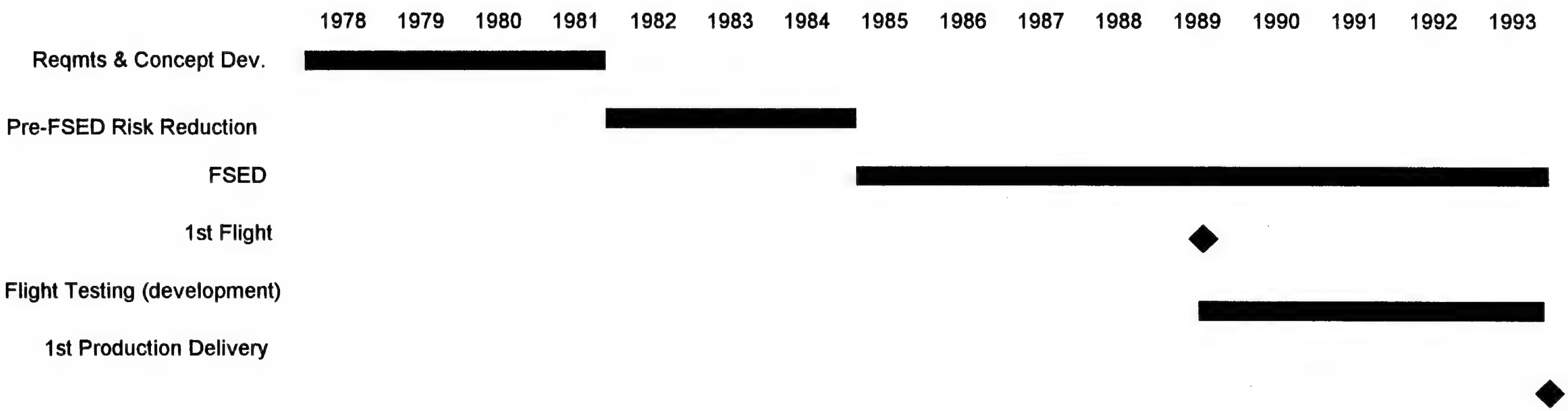
The Air Force conducted concept development from 1978 to 1980 of what was initially called the Advanced Technology Bomber (ATB), the same time the F-117 Stealth Fighter was undergoing full-scale engineering development (FSED). In 1981, two contractors, Northrop and Lockheed, competed in a source selection to develop the ATB. While Lockheed's proposal included a detailed point design which was almost at preliminary design review stage, Northrop's design was much more conceptual and flexible with much

less detail. [Edward, 1995] According to a government engineer involved in the source selection, the decision was close. However, at the conclusion of the competition in November 1981, the Air Force selected Northrop, one of the largest military aircraft companies in the United States, to further develop the design and take it into FSED.

Despite the radical new design and manufacturing techniques employed in the aircraft, the Air Force and Northrop followed the higher risk overlapping prototype/production concept in an attempt to compress the time from development to initial operation. However, before fully embarking on FSED, the Air Force had Northrop go through a pre-FSED risk reduction phase to address critical technology and producibility issues. [Edward, 1995] This phase ended in May 1984 with the presentation of the preliminary design review.

Although the B-2 program started out on a very tight schedule, it was relaxed somewhat after the B-1 bomber program was reinstated in 1982. With a revised schedule, the first flight of the planned flight test program was scheduled for 1987. However, it did not occur until July 1989, about five years after FSED start. The first production aircraft was delivered to the Air Force for operational deployment in December 1993, nearly two years late. (See Figure 3.3.) This represents an FSED schedule slip of about 25 percent. The delay was caused primarily by a major redesign in

Figure 3.3 B-2 development schedule



1984 and difficulties associated with developing numerous new design and production technologies. [Dornheim, 1988]

The government has paid $17.5 billion in base year 1981 dollars ($24.7 billion in then year dollars) for pre-FSED and FSED activities and the fabrication of six airplanes, five of which will be delivered for operational use after completion of operational flight testing. Another $11.8 billion in base year 1981 dollars ($19.2 billion in then year dollars) is being spent for 15 more, the last which will be delivered in 1997. [CPR, 1993] In addition to Air Force funding, Northrop made close to $2 billion in capital investment. The cost on the cost-plus development contract has about doubled over the original estimate. [Gala, 1994] However, much of the cost growth is due to economic factors related to the extension of the program and is not due solely to unanticipated problems and changes. [CPR, 1993]

When the B-2 FSED contract was awarded to Northrop, the Air Force was planning to purchase a total of 132 development and production units. As a result, Northrop and its major subcontractors and suppliers structured its facilities, tooling, and personnel planning to support a large, long-term capital intensive program. [Scott, 1991c] In 1990, however, the Department of Defense reduced the planned production quantity to 75 based on the receding threat from the Soviet Union and the

aircraft's high cost. Then in 1993, with mounting criticism of the program's costs, Congress capped B-2 production at 20. (See Table 3.3-1.) However, based on only 20 B-2s, the unit cost, which includes development expenditures, is projected to be over $1 billion per aircraft in base year 1981 dollars. However, had the original 132 production quantity remained, the unit cost was expected to be about $330 million in base year 1981 dollars ($525 million in then year dollars). In 1994, the last unit entered production, and the contractors started closing down parts of the production line. Despite its production cap, Congress voted funds for government fiscal year 1995 to keep the B-2 production line viable for another year while it decides whether or not to purchase more.

Table 3.3-1 B-2 Production Quantity Changes

| Year | 1981 | 1990 | 1993 |
|---|---|---|---|
| Planned Production Quantity | 132 | 75 | 20 |

The high cost of the B-2, made significantly higher by government imposed quantity reductions and schedule stretches, is due to its revolutionary aircraft design. The bomber is essentially a flying wing fabricated out of advanced composites and materials to render its cross section nearly invisible to radar. The design is also meant to reduce infrared, electromagnetic, and acoustic detection. The only aircraft with a similar aerodynamic shape was the Northrop YB-49 test aircraft from the late 1940s. The B-2

represents the fourth generation of stealth technology, drawing upon the advances in low observability design, materials, and coatings attained on the SR-71, the Advanced Cruise Missile, and the F-117A Stealth Fighter programs. [Scott, 1990] Like those earlier program, the B-2's early development occurred in complete secrecy.

The primary design challenge for the B-2 program was to attain the desired degree of stealthiness with aerodynamics that would allow needed range, speed and payload to be realized. To help achieve the radar cross section requirements, 900 new materials and processes were developed. [Scott, 1990a] Included were the processes to make the composite wings, the largest single piece composite structures ever built. Furthermore, the B-2's shape was generated with the help of a three-dimensional stealth analysis code run on powerful computers. The resulting aerodynamic design was unique and untried, but 24,000 hours of wind tunnel testing and years of simulator tests before the first flight confirmed the aircraft would be stable. [Scott, 1989a]

The other key challenge was systems integration. The B-2 was intended to be flown and all its numerous, complex elements operated by a crew of two pilots, requiring a high degree of integration and interaction among all on-board subsystems. Within the B-2's airframe is packed a wide array of subsystems, including both off-the-shelf and new technology items. In

addition to four General Electric engines and avionics from a variety of companies, the B-2 has a quadruple redundant electronic flight control system, a weapons delivery system, electronic warfare system, aerial refueling capability, and ejection seats for the crew. The B-2 also incorporates an advanced radar that is a significant technological step in developing active sensors that are compatible with low observable aircraft. [Scott, 1991a] Provisions were made in the B-2 for a third crewmember in case avionics automation did not provide enough workload relief for the two-man crew.

The B-2 development team encountered a range of difficulties. For one, there were a variety of problems in developing a large number of new materials and processes. Also, crew ejection seat development and integration were a significant problem, and it helped delay the initial flight test. Weight increased higher than planned, and it impacted the projected payload/range performance. Delays in fabrication of the first aircraft was caused by problems such as wiring bundles either not being installed or being installed incorrectly. Some of these errors were not discovered until complete electrical checkouts were ready to begin. [Aviation Week, 1988]

Some other troubles were stress discontinuities in the cockpit windscreen and cracking of composite wing leading edge sections. The most publicized event, however, has been the B-2's failure

during flight testing in 1991 to meet the radar signature requirement for a few particular cross sections at a narrow frequency band. The B-2 has hundreds of cross sections of interest which are subjected to thousands of test measurements covering the full, wide spectrum of radar frequency. In the domain where the performance deficiency occurred, the B-2 is already substantially better than the F-117. [Rice, 1991] The Air Force considers the failure minor and not impacting operational effectiveness. [Morrocco, 1994] Furthermore, in order to avert any major design changes that could have been implemented to possibly correct the problem, the Air Force relaxed the requirement.

A major design change did, however, take place earlier in the program. The initial B-2 design proposed by Northrop was intended for high-altitude operations only. However, the Air Force had concerns about future vulnerability as threats and missions changed, and it therefore added a low-altitude mission capability requirement after source selection. This made the B-2 an all-altitude aircraft and gave it more future operational flexibility for nuclear or conventional weapons missions. The redesign resulted in a greater fatigue life, more aerodynamic efficiency, and lower weight. [Dornheim, 1988]

The prospect of flying at low altitudes also increased concerns about bird strikes, resulting in a change in wing leading edge

shape and materials. In addition, the engine installation was altered to protect against bird ingestion. While these changes improved the flexibility of the B-2, the redesign in the middle of development was a major contributor to the two-year slip in program schedule, costing about $1 billion. [Dornheim, 1988]

Much of the B-2 program's early resources were devoted to developing manufacturing technologies necessary to build a bomber with the tight tolerances necessary for a large stealth aircraft. This necessitated implementing a sophisticated three-dimensional computer aided design and manufacturing (CAD/CAM) program, as well as new tool designs and manufacturing capabilities. [Scott, 1990]

This new CAD/CAM system was the prime element of Northrop's advanced development approach. It enabled the aircraft to be defined almost entirely on computer, nearly eliminating paper drawings. This system was also part of a streamlined design-to-production tooling process that was supposed to improve the parts fit of the first units. As a consequence, no full-size mockups or advanced technology prototypes were built since the database served as the master model. The B-2 was the first program to implement a computer-based development system to such a large extent. However, its introduction and development was difficult as errors were discovered.

As a result of the problems in the CAD/CAM system, there were significantly more ill-fitting skin panels during assembly of the first B-2 than expected. Subsequent aircraft, though, had better fitting parts as the design/manufacturing database was refined and updated. [Scott, 1989b]

In addition to design and manufacturing process advances, Northrop also changed how the production workers operated by introducing the Integrated Management Planning and Control for Assembly (IMPCA) system in 1991. It was designed to virtually eliminate paper on the manufacturing floor. Computer terminals at each aircraft work center provide current and accurate diagrams and instructions for all tasks. [Scott, 1991b]

After the drastic reductions in production quantities, some manufacturing and cost efficiency improvements supporting large scale production were not implemented because the low production rates of about 1.5 B-2s per year, down from the projected four aircraft per month, did not justify the cost. Therefore, the production B-2s, like the FSED aircraft, are essentially "handmade." [Gala, 1994]

The B-2 airframe has a service life requirement of 10,000 flying hours, which represents about 20 years in typical service. However, if the forty year old B-52 is any guide, the B-2 will probably be utilized as long or longer. The Air Force recognized

this and had the aircraft designed to survive twice the service life. Furthermore, to demonstrate durability performance, a B-2 airframe was subjected to the equivalent of 40 years of normal flying, of bending, twisting, vibrating, and flexing. Only minor modifications to the design were required as a result of this successful series of tests. [Scott, 1992b]

Despite the high cost, the Air Force operational user, the Air Combat Command, is quite satisfied with the B-2. The B-2 has a range of about 6,600 nautical miles unrefueled and over 10,000 nautical miles with one in-flight refueling, enabling it to reach nearly any place on earth. The aircraft meets the original mission requirements, even though a few of the specification requirements on contract did not. [Gala, 1994]

**Systems Engineering Fundamentals**

A high degree of planning went into developing the B-2. The foundation of this planning was a strong set of requirements at the beginning of the program. As the customer, the Air Force was responsible for defining what the ATB, later the B-2, was supposed to be able to do. The top level requirements were developed in response to the Air Force Mission Needs Statement (MNS), the formal document approved by the Joint Requirements Oversight Council (JROC) and the Chief of Staff of the Air Force (CSAF), indicating an actual or projected operational deficiency.

Using this document and the input from the user at the time, the Strategic Air Command, the Air Force developing organization defined a set of performance requirements in a draft system specification that was given to the two competing contractors. This system specification focused on performance and stayed away from functional requirements, giving the contractors greater flexibility in defining a design solution. The B-2 program was one of the first large Air Force programs driven primarily by performance requirements specifications. [Edward, 1995] A consequence of this was a smaller number of engineering change proposals during development than normal.

To help develop detailed requirements, Northrop and the Air Force used a variety of modeling and simulation programs covering threat assessments, performance objectives, and affordability. [Modeling and Simulation Users Survey, 1994] The detailed requirements were documented, but this was done mostly by Northrop, not the government.

Since Northrop did not have many details of the F-117 to use as a guide, the company used the results of the threat simulations and drew upon its prior work in the area of low observability, primarily its three-dimensional radar cross section code, to form its design concept. The eventual concept was broken down in a structured manner into a work breakdown structure, as is normally required at the beginning of an Air Force systems development

effort. This decomposition approach, which addressed both product and functional issues, helped guide the definition of interfaces and the allocation of requirements for the incipient system design. Northrop provided its initial version of this decomposition as part of its proposal to the government, and it updated it as necessary throughout development. Furthermore, the company established reliability requirement allocations early in the program. [Edward, 1995] These allocations were essential in helping identify candidate alternatives.

As part of source selection, the Air Force evaluated and chose between two design concepts. Even before then, however, Northrop had gone through a process of evaluating alternatives itself. Using computer models, Northrop was able to assess a variety of design approaches by running a series of iterations and evaluating the performance and cost tradeoffs. The refined concept is what was proposed to the Air Force. In addition, alternative subsystem design approaches and parameters were evaluated using computer simulations and analyses throughout B-2 development.

Along with performing design tradeoffs, Northrop also had to decide where the parts or software items would be produced. Since Northrop was primarily an experienced aircraft integrator, it did not possess all the design and manufacturing capabilities necessary to perform the effort by itself. For example, it was

not in the business of developing and building engines. Therefore, it was predisposed to purchase many items outside of the company and its Boeing and LTV partners. Furthermore, as a classified program, there were limitations as to where components and subsystems could be obtained. While the B-2 make-or-buy decision process was constrained, is was carried out as required by the government, and it resulted in a large number of subcontractors and suppliers.

When it came to validating B-2 requirements, both the Air Force and Northrop had major roles. The Air Force followed its formal procedure for validating requirements, and it culminated in the approval by the JROC and the CSAF of the Advanced Technology Bomber MNS and later an operational requirements document as discussed previously. Northrop's validation activities to determine if a real world solution existed centered around a variety of threat and low observables simulations that were continually refined throughout development. An aircraft with the survivability characteristics of the B-2 had never been built before. The F-117, a good guidepost, was much smaller and with less low observable performance than that sought for the B-2. Whether or not the B-2 design could be made to perform at a level completely effective to the customer was an issue that required evolutionary requirements definition and evaluation throughout requirements development and concept development phases.

To help determine conformance of the B-2 design to performance requirements, Northrop's team and the Air Force conducted a large amount of testing. As part of Northrop's verification strategy, the company developed sophisticated laboratories to perform component and subsystem testing early in the development process. Nearly a million hours of test time accumulated through environmental stress screening, ground avionics testing, and flights of a C-135 avionics testbed. Extensive wind tunnel, avionics, flight controls, computer systems, qualification, and acceptance testing greatly reduced the number of program unknowns, despite the extensive use of new materials, technologies, and manufacturing processes. [Scott, 1990] The final result of these efforts was early elimination of many reliability problems that normally arise during flight testing and initial operational service. [Scott, 1992a]

The B-2s extensive four year development flight test program involved six aircraft, five of which were planned for eventual delivery as operational units. These B-2s were instrumented for testing during manufacturing and assembly. Focus of the testing ranged from envelope expansion to avionics, comparable to a commercial aircraft flight test program. However, the program also included military specific tests involving defensive avionics, advanced radar, electromagnetic compatibility, and low observables. About a quarter of flight testing was devoted to low observables performance verification.

Northrop also planned from the beginning a very extensive ground durability and structural test series of the B-2 airframe that was conducted parallel to flight testing. Two complete B-2 airframes without engines and electronics systems were built for the sole purpose of conducting these tests. The durability test unit demonstrated two full service lifetimes of vibration and flexing with no major structural damage, and the static test unit demonstrated structural integrity at 150 percent of design limits. [Scott, 1992b]

With the great complexity of the B-2, keeping track of and controlling the interfaces and design configuration was of critical importance. Since the B-2 design was in a three-dimensional digital database, both engineering and manufacturing worked with the same drawing data base. Furthermore, Northrop had formal procedures for controlling changes. As a result, Northrop performed effective configuration status accounting and control. Interface control, however, was somewhat more difficult. The digital database did not have the ability to automatically identify interferences between components. However, it did serve as a forcing function to help highlight the need for interface control and served as the basis for those activities. [Edward, 1995]

As discussed previously, the early involvement by manufacturing in the B-2 was critical since a large number of the advanced

features of the design were process dependent. For many of these items, practical manufacturing methods did not exist at the beginning of the program. Methods were developed and were used to produce the development hardware. Later in development and production, some of the methods and processes in the program were refined to reduce cost. In fact, the Air Force funded manufacturing improvements to decrease machining time for some parts and produce others in less expensive materials. [Scott, 1991a]

In addition to focusing on manufacturing process development early in the effort, there was the critical need to manage the complex integration of the subsystems and components into the airframe. This was done through a methodical approach with sufficient up front planning. Before performing detailed integration, Northrop first had to complete the Air Force's mandated pre-FSED risk reduction to address ten critical issues. They included low observables performance, the fabrication and use of large composite sections, and engine inlet compatibility. None of the items were show-stoppers, and all were addressed to the Air Force's satisfaction. [Edward, 1995]

FSED was then allowed to proceed, and systems integration activities were conducted primarily by Northrop with its subcontractor team members. Northrop's personnel were organized along strict functional lines, but they worked together to

address interdisciplinary issues in a loose structure centered around zones of the aircraft. This zone management worked during development and mainly involved engineering and supportability personnel, but not non-technical workers. The zone leader was essentially the crew boss and helped coordinate the activities of the group. This interaction mechanism was significantly enhanced by the existence of the three-dimensional CAD/CAM database. The digital database served as the master model and forced good coordination between the members working in a zone. Despite the use of this informal structure that evolved during the early period of the program, B-2 development was still driven functionally. Furthermore, the people formally empowered to carry out development and integration activities were program and functional engineering managers, not the zone managers. [Edward, 1995]

Northrop's development approach included the conduct of design reviews, as required by the Air Force. The contractor generated a program management plan, but it was the Air Force that produced the initial systems engineering management plan. Also, the company did not have a separate systems engineering organization. The Air Force B-2 System Program Office (SPO) had one, and it included a team performing independent performance analyses. The SPO encouraged Northrop to create its own systems engineer office, but it did not, choosing to keep the activities distributed in the functional organizations. [Edward, 1995]

Life cycle considerations were taken very seriously during B-2 development. In fact, there was heavy supportability emphasis during requirements definition, and representatives from the Air Force's organization responsible for maintaining aircraft, Air Force Logistics Command, were deeply involved from the very beginning. The Air Force imposed strict reliability and maintainability requirements on the contract, and Northrop was required to present its plan for dealing with the issues in the Reliability Program Plan and the Integrated Logistics Support Plan. Also, the Air Force placed a high level of emphasis on supportability testing, which primarily involved ensuring that the maintenance manuals agree with the aircraft configuration and actual procedures. [Scott, 1991d] This approach gave logistics testing and flight testing near-equal priorities. [Aviation Week, 1991]

Some outcomes of this focus on supportability were that (1) a flight simulator was ready to use before the first flight, (2) the B-2 was the first new Air Force aircraft to enter service with maintenance manuals available upon delivery of the first unit, and (3) the projected maintenance man-hours per flight hour is expected to be considerably less than the requirement. [Scott, 1992a]

Keeping proper emphasis on life cycle issues was one job of Northrop's program managers. To do this, the company appears to

have maintained a reasonably strong program management function in a classified environment to keep track of progress on the tremendously complex aircraft. Computer-based schedules were used, and an effective cost reporting system was in place.

Program management also held a series of regular program reviews. Early in the program, they were quarterly and located at the different contractor locations. Later, they became less frequent and more issue related as the detailed design took shape. The program managers did not, however, use these meetings to usurp the responsibility of the design managers to maintain oversight over the details of their technical areas. [Edward, 1995] This reflects the cooperative environment inside the secret development world of the B-2.

**Development Environment**

As a large military program, the B-2 was developed with the close involvement of government representatives. These Air Force and civil servant personnel from the B-2 SPO and the Air Force Plant Representative Offices oversaw all aspects of development, and the Air Force's user and maintainer organizations interacted heavily with the contractor team from the beginning. Also, the B-2 program represented a large piece of Northrop Corporation's income, and the cost plus development contract included an award fee which incentivized the contractor to be responsive to the Air

Force. Therefore, Northrop and its subcontractors could not help but emphasize the Air Force customer.

The contractors looked to the Air Force primarily for performance requirements that would not change. Early in the B-2 program, however, there was a major change with significant consequences. As previously mentioned, the Air Force added the requirement soon after source selection that the B-2 have all altitude capability to ensure future flexibility, instead of having only high altitude capability as Northrop proposed. Then in 1983 during pre-FSED, extensive structural analysis by contractor and Air Force engineers indicated loads were significantly higher than originally believed. This initiated a redesign to the trailing edge. Early in 1984, fatigue and structural problems associated with the low altitude mission profiles were discovered as the result of analysis. This resulted in moving the cockpit thirty inches. These design changes were made before FSED and hardware fabrication, but they did have significant cost and schedule impacts.

As in other large, complex aircraft programs, B-2 changes have been introduced on the production line, thereby creating different production configurations. The B-2s are separated into three blocks representing configuration sets. Block 10 and Block 20 have a total of 18 B-2s, and Block 30 has two. The Block 30 configuration reflects features and performance the program

originally sought, and the 18 other aircraft will be retrofit with the capability at the completion of unit 20.

The majority of B-2 development occurred while the program's existence was classified. This situation shielded the effort from Congressional and public scrutiny and contributed to an environment of funding and political stability, as well as workforce-level stability. This enabled the developers to concentrate on designing the aircraft instead of constantly justifying the program. The Air Force did not have problems obtaining funding for the B-2 until late in development after the program was publicly acknowledged in 1988. While Congress was very supportive when the B-2 was a classified program, political pressures had changed some lawmakers' positions. As the Cold War ended, pressures to reduce military expenditures prompted major quantity reductions of the B-2. Furthermore, the rising unit cost of a shrinking B-2 production program have been widely reported and criticized in the media. In the early 1990's, the impact of this reduced political support was stretched-out production and the gradual reduction of the workforce-level. Although production funding has been severely restricted, development funding was never significantly impacted.

Along with stable FSED funding, the B-2 also possessed a high degree of continuity among key managers and engineers from early development to production. Contributing to this stable

environment, the Air Force B-2 SPO maintained unusual continuity in its leadership, keeping the same military program director in place from 1983 to 1991.

The constancy of the core development team mirrors a stable contractor organizational structure throughout development. As mentioned previously, Northrop's leadership of the B-2 contractor team had a strong functional orientation which was reflective of the way the company has been traditionally organized. While the structure worked reasonably well, the Air Force program directors were looking to change to an integrated product development (IPD) approach which would formally establish interdisciplinary integrated product teams and force business and technical issues to be worked together. IPD was implemented in 1991, when the majority of development was complete. Northrop, however, has resisted fully adopting IPD. With the program starting to close down, the Air Force decided not to enforce full compliance. [Edward, 1995]

While one aim of IPD is to improve the level of interaction and cooperation across functions and organizations, a spirit of cooperation was already evident within the B-2 team early in development, according to two government engineers involved since source selection. In their opinion, the relations among the Air Force, Northrop, and the subcontractors were very good overall.

They claim there was free and open dialogue, and that the team viewed everyone as true partners. They also commented that the contractors were not afraid to identify problems, and they took a proactive approach to propose solutions. [Edward, 1995]

The degree of team communication and coordination, therefore, appeared to be reasonably high despite the fact that the team was widely scattered throughout the country. Furthermore, very tight security requirements made simple phone calls and mailing packages difficult, and there was no computer link between sites initially. Much of the interaction came as a result of many on-site meetings throughout the country. In addition, the three-dimensional CAD/CAM digital database was very useful, and it provided the basis of effective technical interaction at many of these meetings.

Once the B-2 became publicly acknowledged, security procedures were relaxed that allowed old communication means to be reestablished and new ones to be implemented. An important new link established in 1992 was the Logistics Support Management Information System, a computer network connecting Northrop with subcontractors, suppliers, and the Air Force's supportability centers and users. [Scott, 1992a]

The widely scattered team members recognized what their responsibilities were. Northrop was the prime integrating

contractor with overall responsibility to the Air Force to make the system work. This included the engine, which the Air Force was responsible for developing and buying directly from General Electric. The various subcontractors were responsible for their respective subsystems, and they understood to whom they reported at Northrop. The zone management structure described earlier, though not a formal organization with documented relationships, worked reasonably well due to the cooperation of the team members.

The ability of any group to perform work on the B-2 was greatly impacted by the security requirements. One of the biggest problems in conducting the program was getting people security clearances in a reasonable amount of time, since it could sometimes take a year. However, once that hurdle was crossed, the B-2 program offered a high degree of flexibility and autonomy in conducting the design work. This was despite the fact that the Air Force had a SPO of several hundred people overseeing the effort. They were not a major hindrance because the Air Force implemented streamlined management techniques. Instead of imposing detailed functional specifications, top-level performance specification were imposed. Many military standards were either heavily tailored or else presented as guidelines. In addition, members of the Air Force SPO worked well with the contractors in general, and they added value by being the interfaces in areas that required government input. As one

example, the systems analysts from the B-2 SPO worked closely with the contractors to help identify and solve technical issues, and they were viewed as contributing members and not as threats. [Edward, 1995]

An effort with the national importance, technical challenge, and budget of the B-2 warranted that the organizations involved place their best people on it. Northrop did this by appointing its top aircraft designer to lead the technical effort. Further motivation for Northrop was that as prime contractor, it had total system performance responsibility, thereby making it contractually accountable to the Air Force. Furthermore, as a cost plus contract with award fee, profit during development was dependent on how well Northrop performed on a yearly basis. Perhaps most importantly, the Department of Defense required extensive performance and workmanship warranties be placed on Northrop to enforce accountability.

**Summary/Conclusion**

The B-2 is a very complex and expensive system whose extended development was conducted in accordance with systems engineering fundamentals in the relative stability of the world of classified military programs. Northrop's paperless development approach using a three-dimensional CAD/CAM system contributed to that

stability, and it pioneered, despite shortcomings, the new direction of aerospace development. This breakthrough design combines both existing and advanced technologies in a highly integrated yet supportable stealth package with the capability to perform intercontinental nuclear and conventional weapons missions for the Air Force well into the twenty-first century.

Table 3.3-2 B-2 Performance scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| TECHNICAL PERFORMANCE - INITIAL | 0-10 | 1 | 8 | 8 |
| TECHNICAL PERFORMANCE - MATURE | 0-10 | 1 | 9 | 9 |
| COST PERFORMANCE | 0-10 | 1 | 3 | 3 |
| SCHEDULE PERFORMANCE | 0-10 | 1 | 4 | 4 |
| PERFORMANCE TOTAL | | | | 24 |

Table 3.3-3  B-2 Systems Engineering Fundamentals scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| REQUIREMENTS DEVELOPMENT | 0-10 | 2 | 8 | 16 |
| INCIPIENT SYSTEM DESIGN | 0-10 | 2 | 8 | 16 |
| EVALUATING ALTERNATIVE CONCEPTS AND DESIGNS | 0-10 | 1 | 10 | 10 |
| MAKE-OR-BUY DECISION | 0-10 | 1 | 9 | 9 |
| VALIDATION | 0-10 | 1 | 9 | 9 |
| VERIFICATION AND INTEGRATED TESTING | 0-10 | 1 | 10 | 10 |
| CONFIGURATION MANAGEMENT | 0-10 | 1 | 7 | 7 |
| MANUFACTURING CONSIDERATIONS | 0-10 | 1 | 9 | 9 |
| SYSTEMS INTEGRATION AND TECHNICAL MANAGEMENT | 0-10 | 1 | 7 | 7 |
| LIFE CYCLE CONSIDERATIONS | 0-10 | 1 | 10 | 10 |
| PROGRAM MANAGEMENT | 0-10 | 1 | 7 | 7 |
| SYSTEMS ENGINEERING FUNDAMENTALS TOTAL | | | | 110 |

Table 3.3-4 B-2 Development Environment scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| EMPHASIS ON THE CUSTOMER | 0-10 | 1 | 9 | 9 |
| STABILITY OF REQUIREMENTS AND CONFIGURATION | 0-10 | 1 | 3 | 3 |
| FUNDING AND WORKFORCE-LEVEL STABILITY | 0-10 | 1 | 9 | 9 |
| STRONG SUPPORT FOR PROGRAM | 0-10 | 1 | 6 | 6 |
| CONTINUITY OF CORE DEVELOPMENT TEAM | 0-10 | 1 | 8 | 8 |
| STABILITY OF ORGANIZATIONAL STRUCTURE | 0-10 | 1 | 9 | 9 |
| COOPERATION AMONG ALL STAKEHOLDERS | 0-10 | 1 | 9 | 9 |
| EFFECTIVE COMMUNICATION WITHIN TEAM | 0-10 | 1 | 7 | 7 |
| FLEXIBILITY AND AUTONOMY | 0-10 | 1 | 7 | 7 |
| WORKFORCE EXPERTISE AND EXPERIENCE | 0-10 | 1 | 8 | 8 |
| ACCOUNTABILITY FOR SYSTEM PERFORMANCE | 0-10 | 1 | 7 | 7 |
| DEVELOPMENT ENVIRONMENT TOTAL | | | | 82 |

Table 3.3-5 B-2 Design Difficulty scores.

| Elements | Range | Score |
|---|---|---|
| TYPE | 0-15 | 13 |
| KNOWLEDGE COMPLEXITY | 0-10 | 8 |
| STEPS | 0-10 | 9 |
| QUALITY IMPLEMENTATION EFFORT | 0-10 | 8 |
| MANUFACTURING OPERATIONS IMPLEMENTATION EFFORT | 0-5 | 5 |
| SELLING PRICE CONSTRAINT | 0-5 | 1 |
| DESIGN DIFFICULTY TOTAL | 0-55 | 44 |

Table 3.3-6 B-2 Resources scores.

| Elements | Range | Score |
|---|---|---|
| COST | 0-15 | 12 |
| TIME | 0-10 | 8 |
| INFRASTRUCTURE | 0-10 | 8 |
| RESOURCES TOTAL | 0-35 | 28 |

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Telephone interview with John Gala, Deputy Director of Enginering, B-2 System Program Office, Wright-Patterson AFB, Summer 1994.

Telephone interview in February 1995 with former and current members of the B-2 System Program Office, Wright-Patterson AFB, Ohio:

Don Edwards. Former Chief of Flight Systems Engineering. Participated in source selection in Fall 1980. Joined the program in late 1981 and left in 1987.

Mark Wilson. Chief of Structures until 1993. Now Chief of Flight Systems Engineering. Joined the program in late 1980 after contract award.

John Gala. Deputy Director of Engineering. Joined program in 1992.

## 3.4 CASE STUDY: MCDONNELL DOUGLAS C-17 MILITARY TRANSPORT

The McDonnell Douglas C-17 is the latest Air Force aircraft developed to meet airlift requirements for the Air Force, Army and Marine Corps. The C-17 is intended to carry large cargo over intercontinental distances and deliver it on short, unpaved runways. The aircraft is also expected to require only minimal ground support, need only a small parking space, be able to airdrop troops and equipment, and operate with a crew of only two pilots and a loadmaster. The need for such a versatile aircraft was highlighted by the failed Iran hostage rescue attempt in 1980 which exposed the lack of sufficient mobility to respond quickly to emergencies in remote locations. [McCloud, 1993] Furthermore, the C-17 is needed to replace the 30 year old C-141 Starlifter fleet that is planned for retirement before the year 2000. Although most of the subsystems of this original design utilize proven, off-the-shelf technology, this complex aircraft has faced a number of integration, performance, and management problems during its long development.

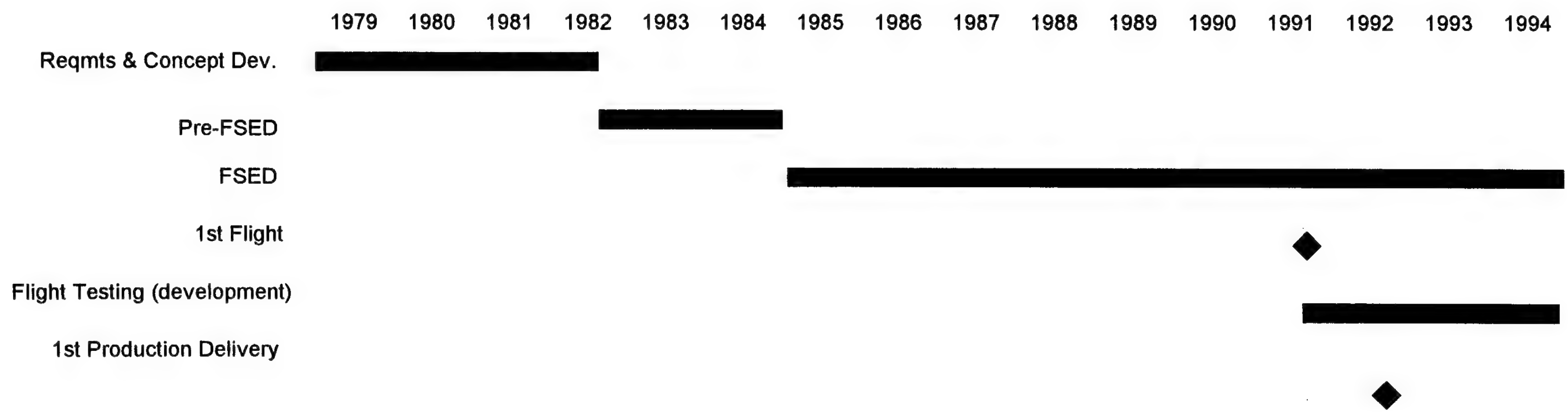
### Development History, Design, and Performance

The Air Force issued a request for proposals (RFP) to aircraft development contractors for a new airlifter in late 1980. In August 1981, Douglas Aircraft - Government Segment, a company in the McDonnell Douglas Corporation, was selected prime contractor

for the then called C-X program in a competitive source selection. However, contract award and the start of work were put on hold since the Air Force had just been authorized by Congress to build more C-5 and KC-10 cargo aircraft, thereby diminishing the immediacy of the C-17 effort. A year later, the Air Force awarded the $6.6 billion fixed-price full-scale engineering and development (FSED) contract that included options for six initial production units as part of a concurrent development/production strategy. However, Douglas was funded at a low level, only about $30 million a year, for three years for advanced technology development and pre-FSED activities. Not until late 1985 did the government finally fund Douglas to begin FSED. With this delayed start date, the Air Force expected production to begin by 1988, the first flight to occur in August 1990, and initial operational capability of 12 aircraft in early 1992.

In January 1988, the first production contract option was exercised according to schedule. However, the first flight did not occur until 15 September 1991, over a year late. The first production C-17 was delivered to the Air Force for operational testing in September 1992, and more than fifteen aircraft have been delivered to the Air Force so far. Developmental flight testing was completed in December 1994, and the C-17 was declared operational in January 1995, three years after the originally projected date and fourteen years after Douglas won the source selection. (See Figure 3.4.)  This represents an FSED schedule

Figure 3.4  C-17 development schedule



delay of about 35 percent when compared to its projected length when it began in 1985.

Along with the stretch in schedule came an increase in costs. The fixed-price development effort has an overrun of $571.3 million on $3.499 billion stated in base year 1981 dollars. [DAES, 1994] This represents an overrun of approximately 16 percent. Since the C-17 was developed on a fixed-price contract, McDonnell Douglas is liable for the overrun.

The unit price of the C-17, which takes into consideration the cost of development, depends to a large degree on the quantity the Air Force purchases. Normally, the larger the quantity, the lower the unit price. The planned number of C-17s to be acquired, though, has been drastically reduced since program start. Originally, the Air Force planned to purchase 210 aircraft. However, due to delays, technical difficulties, and perceived capability reductions, Congress reduced the buy to 120 in 1990. Congress then decided to limit production to 40 units in 1993. (See Table 3.4-1.) while alternatives to the C-17 are investigated. Additional aircraft could be purchased if Douglas can resolve performance, cost, and schedule problems by the end of 1995. Based on the purchase of 120 aircraft, the unit cost is projected to be about $300 million (then year dollars) or $144.5 million (base year 1981 dollars), which includes development costs, but not initial spares, modifications, and outyear

operations and maintenance support. However, if production is limited to 40 aircraft, the unit cost of the C-17 is estimated to be $408 million per aircraft (then year dollars) or $219 million (base year 1981 dollars) [DAES, 1994]

Table 3.4-1 C-17 Projected production quantity changes.

| | 1985 | 1990 | 1993 |
|---|---|---|---|
| Projected Production Quantity | 210 | 120 | 40 |

As the high costs suggest, the C-17 has a lot of capability. It is a large aircraft with the length of the Air Force's medium airlifter (C-141) and the fuselage width of the heavy airlifter (C-5). It is propelled by four Pratt & Whitney engines which are essentially the same as those used on the Boeing 757 since 1984. It contains many of the same features found on large commercial airliners, such as advanced, highly integrated avionics and fly-by-wire flight controls. Being a military aircraft, it also includes non-commercial features, such as air refueling capability to increase range, defensive avionics, the ability to takeoff from and land at small austere airfields, the capability to backup and park unassisted, and a complex cargo handling system that enables offloading by a single person. The C-17 was designed to carry palletized cargo and heavy, oversized items, such as a large battle tank or three attack helicopters, in a single load. In addition to its cargo transport role, the C-17

must also be able to perform medical evacuation and paratrooper airdrop. In essence, the C-17 represents the merging of capabilities of the existing large and small Air Force airlifters that perform a wide range of missions.

Even though the C-17 is an expensive and very complex aircraft, its development was originally conceived as a low-risk venture, in which technology proven on other aircraft would be integrated together in the new airframe design. But integration of the features on a single aircraft of the size and intended versatility of the C-17 turned out to be a much greater undertaking than Douglas officials had anticipated. [Smith, 1993b]

The C-17 was designed to be highly automated to enable operation of all flying and avionics system duties without a third person. This was made possible by 44 interconnected computers controlling and integrating all the aircraft's subsystems. Understandably, avionics integration has been the leading technical challenge, with primary emphasis on the mission computers. [Gilmartin, 1990] There are three identical mission computers in the C-17, and there had been some difficulty getting them into synchronous operation due primarily to software problems. Because of these and other technical and schedule difficulties, Honeywell, the subcontractor in charge of designing and developing the avionics suite, was dropped in 1989, and General Electric was brought on

board with a different, more complex design. [Scott, 1991]

The C-17 program is replete with other examples of design challenges and difficulties. One of them concerns the wings. The wings were not initially considered a major design challenge, but they became a large, expensive problem. The full-size structural test vehicle failed the wing structural 150 percent load tests at 128 percent of test load limit in October 1992. The failure was discovered to be the result of an inadequate design caused by (1) a computational error by the Douglas engineers, (2) optimistic assumptions, and (3) high and uneven distribution of the test pads on the wing. [Lynch, 1993] The structural test vehicle with a temporary modification to the wing failed the test again in September 1993, this time at 144 percent of test load limit. A new, permanent design judged to be operationally safe and technically sound by an independent consulting team was developed and successfully tested in January 1994, and it was incorporated into the production line.

Other major design challenges have been to keep weight growth to a minimum and to get the commercially derived engines to meet fuel consumption requirements. The current weight is about three percent above the original allocation, and the Pratt & Whitney engine fuel efficiency is 2.8 percent below original projections. [DAES, 1994] Both of these deficiencies have impacted payload/range performance.

In addition to a considerable number of design problems, difficulties with Douglas's manufacturing operations have contributed greatly to cost increases and schedule delays. In the first years of the C-17 program, Douglas's production system was very inefficient. Inaccurate or outdated engineering drawings led to thousands of manhours spent on doing rework and repair out of position on the assembly line, thereby adding costs and delaying deliveries. [Lynch, 1994a] These problems were compounded by a variety of quality related issues, such as faulty rivet machines, flawed composite flight control surfaces, and out-of-round fuselage cross-sections. Douglas, however, did not make significant improvements to its production operations until the early 1990s.

As a result of the technical problems experienced, the C-17 does not meet all of its original or current performance requirements as demonstrated in extensive flight testing using production aircraft. Among them is the payload/range performance, whose shortfall can be attributed to aircraft weight increase, engine fuel efficiency shortfall, and increased aerodynamic drag. This requirement has gone through great changes since the beginning of the program. However, the C-17's shortfall in this area does not reflect a high degree of customer dissatisfaction.

The initial Air Force requirements, as contained in the request for proposal in 1980, called for the new transport to carry a

maximum of 130,000 lb. of cargo for an undefined unrefueled range, later suggested at 2,400 nautical miles. The document also expressed the Air Force's goal of carrying a maximum cargo load of 160,000 lb. In its proposal, Douglas claimed that its aircraft would carry up to 167,000 lb. of cargo an unrefueled range of 2,400 nautical miles. Douglas won the competition and agreed to an official increase in the specification payload requirement to its higher proposed value of 167,000 lb.

As the C-17 development progressed, it became apparent to Douglas and the Air Force that some of the requirements, including payload/range, would not likely be met. This appears to have caused the Air Force to reevaluate the performance requirements on the C-17 contract to see if they were appropriate. The 1989 review of requirements to determine if the C-17 was overspecified resulted in the relaxation of the specification requirement to 160,000 lb. for the 2,400 nautical mile mission. However, the production C-17s tested in the early 1990s did not meet the revised requirement, either.

In 1993, the Air Force reviewed the C-17 requirements again in light of the end of the Cold War. Based on reduced wartime airlift requirements for Europe, it established a new requirement of 157,000 lb. for 2,400 nautical miles, and established a new key requirement parameter of 120,000 lb. for a 3,200 nautical mile mission with a 110,000 lb. threshold. These changes were

part of a broad contractual settlement in which Douglas agreed to drop monetary claims against the government, invest more money in the C-17 program, and improve its management. A summary of the payload/range requirements changes is shown in Table 3.4-2.

Other original specification requirements and goals were relaxed as part of the 1989 review, with minimal impact to capability. These included changing the launch response time from five minutes to 15 minutes (the same requirement on the C-141) as well as relaxing about three dozen less-significant contract specifications. [Morrocco, 1991] The Air Force operational users reviewed performance requirements again in 1993 and changed many to objectives. [Morrocco, 1994]

The Air Force had the contractual authority to require full compliance with the performance requirements. However, keeping to the original specifications would have forced a switch to even more powerful engines, thereby eliminating its commonality with commercial airline engines and adding to future maintenance costs. [North, 1993] Furthermore, this modification would have delayed the program even further, thereby threatening the continuation of the program and therefore the means to fulfill projected airlift requirements.

| Subject | Original RFP 1980 (lb.) | Original Spec 1982 (lb.) | FSED Start 1985 | Revised Spec 1989 (lb.) | Revised 1993 (lb) |
|---|---|---|---|---|---|
| Maximum Payload | 160,000 | 172,200 | | 172,200 | 169,000 |
| Maximum Payload Mission (2,400 NM) | 130,000 | 167,027 | | 160,000 | 157,000 |
| Heavy Logistics Mission (2,400 NM) | 120,000 | — | | — | — |
| Heavy Logistics Mission (2,700 NM) | — | 150,000 | | 150,000 | 145,000 |
| Heavy Logistics Mission (3,200 NM) | — | 130,000 | | 130,000 | 110,000 |
| Intertheater Logistics Mission (distance TBD) | 100,000 | — | | — | — |
| Intertheater Logistics Mission (2,800 NM) | — | 124,039 | | 120,000 | 114,000 |
| High Performance Logistics Mission | 70,000 | 81,140 | | 74,987 | 74,987 |
| Ferry Range | 5,000 NM | 4,915 NM | | 4,600 NM | 4,300 NM |

Table 3.4-2 C-17 Requirements/Specification Changes.

Compiled from System Specification for C-17 Airlift System, 1 Sep 90; Defense Acquisition Executive Summary (DAES) Report for C-17, 25 Jul 94; Aviation Week, 9 Sep 91; Aviation Week, 3 Jan 94.

In addition to issues surrounding payload/range requirements, there have been questions about reliability and maintainability performance. Both are areas with long-term implications for the Air Force. The C-17 was failing by a substantial margin to meet three system specification requirements for reliability in developmental and initial operational flight testing. They were Mean Time Between Removal (MTBR), Mean Time Between Maintenance - Inherent (MTBM(I)), and Mean Time Between Maintenance - Corrective (MTBM(C)). Not meeting MTBR could increase the quantity of spares required, and not meeting the system MTBM requirements could affect resources to support the system. During the last half of 1994, however, the reliability of the C-17 demonstrated in operational flight testing dramatically improved and was meeting or exceeding system specification growth curve requirements. [EPMR, 1994] Meanwhile, demonstrated maintainability performance, measured in Maintenance Man-hours per Flying Hour (MMH/FH) and Mean Man-hours to Repair (MMTR), continued to be better than the growth curve requirements, and the C-17 has been meeting its Mission Capable (MC) Rate and largely surpassing its Mission Completion Success Probability (MCSP) requirements. [EPMR, 1994] Douglas and the Air Force expect improvements to continue, leading up to the July 1995 Reliability, Maintainability, and Availability Evaluation, a critical hurdle which will help determine if additional C-17s will be built.

The C-17 has either demonstrated or is expected to meet most if not all the performance requirements. Attaining them will provide the Air Force a significantly enhanced airlift capability over what it currently has. The Air Force customer expects the C-17 will be adequate for its operational needs and considers it the most cost effective solution to meeting military airlift requirements. [Morrocco, 1994b]

As described earlier, mission flexibility was designed into the aircraft, and it is a key element in the Air Force's criteria for satisfaction with the C-17. The design incorporates lessons learned from the operational experience of the current Air Force airlifters, the Lockheed C-141, C-5, and C-130. This has resulted in a design with great cargo handling versatility. Cargo handling items that are optional on other aircraft are standard equipment on the C-17. Although this versatility increased weight and consequently decreased potential payload/range capability, the Air Force accepted this tradeoff to ensure the mission flexibility was always available to each aircraft. [Dornheim, 1993]

The Air Force also expects the C-17 to be in operation a long time. According to the C-17 Prime Item Development Specification, "The C-17 airframe service life shall be 30,000 flight hours. Utilization shall be based on the mission profiles contained in the C-17 System Specification. The airframe shall be designed for twice the service life." It continues, "The C-17 shall have a

useful life of not less than 30 years under any combination of operating service and storage life, when operational service life has not been exceeded." As current Air Force aircraft in service attest, particularly the B-52, C-141, and C-130, 30 years is a realistic length of time to expect the aircraft to operate. Obtaining a C-17 design to achieve that long life and flexibility has been a long and difficult process.

**Systems Engineering Fundamentals**

McDonnell Douglas is one of the world's largest developers of military and commercial aircraft. Over the past thirty years, it's companies have built a wide range of successful jets, including the DC-8, DC-9, and DC-10 passenger transports, the F-15 and F/A-18 fighters, and the KC-10 cargo transport and aerial refueling aircraft. During this time, McDonnell Douglas had followed a traditional approach to aircraft development. This method, supported by a functionally oriented organizational structure, was characterized by a high priority placed on design engineering activities with minimal influence of manufacturing design concerns.

Since the C-17 is a military aircraft, the Air Force was closely involved in most aspects of Douglas' development activities. As the customer, the Air Force defined its requirements for what would become the C-17 in a formal process that normally

culminates in the issuance of a Mission Need Statement (MNS) and a document defining operational requirements. The MNS certifies that an operational need exists and defines it. The requirements generated from the Air Force airlift study in 1980 formed the basis of the top level mission requirements in a MNS for what was at that time designated the C-XX aircraft. Operational performance requirements were defined afterwards by the Air Force, and these were used to define system requirements in conjunction with Douglas. They were formally documented in a system specification and a prime item development specification. As previously discussed, Douglas allowed a more stringent specification to be imposed than what the Air Force originally suggested. This was probably done by Douglas as a way to help win the contract source selection. However, it had long-term negative impacts for the program.

Douglas had modeled its C-17 system concept using previous transport and research aircraft as guides. The next step was to follow a structured approach to decompose the elements of the complex system into a work breakdown structure (WBS), as is normally required at the beginning of an Air Force systems development program. This approach, which addresses both product and functional issues, helps define interfaces and allocate requirements. Douglas provided its initial version of this decomposition as part of its proposal to the government, and it updated the WBS as necessary throughout development.

The Air Force selected among several basic designs from several contractors when it held source selection. Furthermore, during the C-17 concept development phase, Douglas evaluated alternative concepts and designs to come up with one it believed would meet the Air Force's requirements. Douglas continued performing tradeoff studies throughout the pre-FSED effort and into production, as it has attempted to define, improve, or correct the configuration.

Along with performing design tradeoffs, Douglas also had to decide where the parts or software items would be produced. The large number of subcontractors and suppliers on the C-17 contract indicates that the least expensive approach for Douglas was not to do everything in-house. The company has been primarily an aircraft integrator and airframe manufacturer, and it has obtained engines and avionics from outside companies. Douglas's make-or-buy decision process on the C-17, a normal commercial practice in large aerospace firms, was also required by the Air Force contract.

When it came to validating C-17 requirements, both the Air Force and Douglas had major roles. The Air Force followed its formal procedure for validating requirements, and it culminated in the approval by the Joint Requirement Oversight Council (JROC) and the Chief of Staff United States Air Force of the C-XX MNS

discussed previously. On the C-17 program, the Air Force also evaluated the requirements two other times to determine if they were still reflective of the mission. These validation reviews occurred over a thirteen year development period, and they resulted in changes that reflected changing needs. However, such reviews probably would not have occurred if the C-17 had not encountered technical, cost, and schedule difficulties.

As for Douglas, it performed its primary validation activities during concept development before source selection to determine if its concept design was feasible. Douglas reviewed the structural capability of the existing transporters, integrated aerodynamic features it developed in the late 1970s to enable short takeoff and landing, conducted wind tunnel tests of resulting models, and performed other analyses to help determine if a real world system could be built.

Once the C-17 requirements and design concept were validated, Douglas had to verify that what it was developing conformed to requirements. To do this, Douglas used extensive physical mockups of the fuselage and cargo sections to demonstrate equipment placement and cargo handling capability, two structural ground test articles for static and durabilty tests, and a cockpit and avionics bay mockup called the flight hardware simulator for integrated avionics testing on the ground. Also, prior to first flight, each test aircraft underwent the On Ground Aircraft

System Test (OGAST). The OGAST is a hardware-in-the-loop test which simulates aircraft flight on the ground and exercises the aircraft's system components together instead of individually. Additionally, Douglas produced and flew one FSED prototype flight test unit before completing construction of four FSED flight test units that were to be later delivered for operational use. This was all performed in accordance with the Air Force required formal test and evaluation master plan and formal test procedures.

C-17 flight testing was originally expected to be run much like a fast-paced commercial transport program in which Douglas would take the lead. However, the Air Force later decided to manage it. Commercial aircraft test programs typically require 10-14 months, while Air Force test programs generally involve a slower paced approach in order to evaluate safety requirements and previous test data. [Smith, 1993c] Furthermore, military aircraft must conduct additional tests to demonstrate maneuvers and capabilities which are unknown in the commercial world. [Lynch, 1993] In the case of the C-17, technical problems discovered during flight testing also extended the effort. Consequently, the development flight test program which began in 1991 was finally completed three years later.

Because the C-17 has been a highly concurrent development and production program, Douglas delivered aircraft to the Air Force

while still evaluating and modifying the design. Therefore, there was no stable, approved baseline configuration to which the aircraft were being built. As a result, the first twenty-eight C-17s were of widely varying configurations. [Smith, 1993a] Although Douglas had a system for interface and configuration status accounting and control much like that of other large aerospace contractors, it was not effective in tracking so many different configurations. For three months in 1994, the Air Force C-17 System Program Office (SPO) and Douglas formed a special action team to define a stable configuration for the Air Force to declare operational. The team was also chartered to develop a disciplined process to track and status the configuration of each aircraft. [PPR, 1994] The team defined an operational baseline and formed the Integrated Configuration Management Database which provides instantaneous status information to interested program participants.

Some of the configuration changes have been prompted by difficulties experienced on the production floor. While the Douglas manufacturing organization conducted the C-17 production planning, it did not have a large amount of influence with the design engineers. Therefore, the components and assemblies of the C-17 were not designed with ease of manufacturability as a primary design driver. This is partly reflected in the high rework and repair rate, especially on the first C-17s. Forty percent of the labor hours on the first two C-17s went to repair,

rework, and nonstandard work. [Smith, 1993b] As it overran the development contract, Douglas had great financial incentives to recoup the losses during production. Therefore, Douglas started developing and evaluating parts redesigns aimed at reducing the cost of the remaining production units.

While being an expensive aircraft, the C-17 does not advance the state-of-the-art in individual technology areas. It does, however, involve the sophisticated integration of a lot of technologies in a type of aircraft Douglas had not worked on before. Unfortunately, the company failed to conduct adequate early risk assessments on some of these systems. [Morrocco, 1991] Douglas essentially underestimated the extent and complexity of the development effort, and the result has been constant design changes to correct problems and minimize the attendant schedule slips.

Some of Douglas's difficulties can be traced to competing priorities for limited company resources. By the time Congress authorized FSED funding in 1985, McDonnell Douglas was starting to run other major aircraft development programs. In 1987, the company was involved simultaneously in developing the Navy T-45 trainer and the MD-90 and MD-11 commercial transports, as well as the C-17. These four concurrent programs overburdened the resources and talent of a company that had not produced a new aircraft design in over a decade. [Morrocco, 1993] The C-17

program had been drained of the company talent and management attention that had originally been assigned to it before Douglas had won the source selection in 1981. The inadequate allocation of qualified engineering and manufacturing personnel contributed to the design difficulties and led to inefficiency on the manufacturing floor.

To improve its manner of developing aircraft, McDonnell Douglas decided to move its companies from a traditional, functionally oriented development approach to a team-based approach that would improve the interaction between the engineering, manufacturing, and support disciplines. In 1989, McDonnell Douglas attempted to implement its Total Quality Management System (TQMS) corporate-wide, including Douglas. However, it was poorly carried out and disrupted the entire company, thereby slowing C-17 program progress and failing to improve the program's situation.

In order to help resolve the extensive C-17 technical and management problems that continued to face the contractor in the early 1990s, the Pentagon forced McDonnell Douglas and the Air Force to fully and effectively implement an integrated product development teaming approach in 1993 for the completion of C-17 development and production of the remaining units. This involved extending the teaming concept already in place at Douglas to physically locating interdisciplinary team members together and

formally including Air Force personnel. In response, Douglas and the Air Force C-17 SPO established a network of nine integrated product teams, with each of these teams in turn overseeing subordinate teams. [Lynch, 1994a] This arrangement was formally documented in an integrated product team plan. In addition, Douglas was required to implement a paperless design system through use of an advanced computer aided design network, much like that implemented by Boeing during 777 development.

Although Douglas had significant technical and management problems, the company did follow most of the Air Force's required sequence of design reviews and fulfilled most of its required documentation submittals.

Some of these submittals documented how Douglas was going to address a broad range of life cycle considerations, as required by the Air Force. Reliability and maintainability requirements were called out in the system specification with the objective of ensuring mission accomplishment and controlling maintenance costs, and plans addressing these areas were required. However, an aggressive reliability growth program was not implemented until 1994. [DAES, 1994] The Air Force also called for ease of item accessibility to reduce the time and difficulty of repairing and replacing C-17 components, and there was maximum use of built-in test features to reduce maintenance and troubleshooting times. Training was given importance, and Douglas developed a

flight hardware simulator to train flight crews. The result of these efforts were incorporated into a life cycle cost model, which was used by Air Force planners.

The importance of life cycle considerations on the C-17 program is illustrated by the decision to forgo additional efficiency improvements to the engine design in order to maintain its commonality with its commercial counterpart. By doing this, the Air Force expects to save on spare parts costs and possible reliability and maintainability cost increases. [North, 1993]

While supportability concerns have been addressed on the C-17 effort, they have not always prevailed. One design result which may have a negative long term impact is the proliferation of computer languages in C-17 software. Six different computer languages are used throughout the aircraft, and many subsystems contain more than one language. This diversity is likely to result in excessive software maintenance costs in the long run. [Bond, 1992] This approach, however, was consciously chosen to accommodate shorter term schedule and cost considerations. The Air Force plans to eventially convert all software to ADA.

In summary, although not all the outcomes have been commendable, supportability issues did receive a high level of attention throughout C-17 development.

Douglas program management had a difficult time keeping track of the program during most of the C-17's development. In the past, the output of the Douglas cost schedule and control system often lagged sixty days behind factory floor work. [Lynch, 1994b] An independent Department of Defense panel concluded as late as 1993 that Douglas's business systems were struggling to provide the management visibility and control needed to properly support the program. [Lynch, 1994a] Managers therefore did not have the timely management data to help identify problems. Furthermore, the program did not have the Douglas management focus and resources during much of the program to quickly resolve the problems once discovered. With the implementation of the integrated product teaming approach in 1993 came an improved ability to track and manage the program for both Douglas and the Air Force. This included a new, computer based cost and schedule accounting system in which the reports are generated and provided to Douglas management and the government within seven days after the close of the monthly accounting period. A key feature of the new C-17 management operations is that there is only one set of plans, teams, and schedules, and therefore no longer separate government and contractor versions. The improvement in program management effectiveness in the mid-1990s, due in part to the management changes implemented, also followed attendant improvements in the development environment.

**Development Environment**

As is evident from the discussions up until now, the C-17 program did not progress smoothly. Mirroring the discord, and in some cases contributing to the problems, has been a difficult development environment for both the Douglas and the Air Force.

The C-17 was conducted in the manner of a typical Air Force system development program. That is, the Air Force customer was involved in overseeing all aspects of the effort through representatives in the SPO and on-site presence of the Air Force Plant Representative Office (AFPRO). As was typical at the time, the Air Force also specified in great detail what it expected the system to do. Furthermore, the Air Force expects to be kept informed of development progress. Therefore, Douglas could not escape emphasizing the customer. This arrangement, in place during all of development, allowed much input by the Air Force. However, Douglas would not do everything the Air Force wanted done to correct problems due to the overrun on the fixed-price contract.

While the Air Force was obliged to provide guidance on requirements, Douglas was fully responsible for design and fabrication. The Air Force specification requirements had remained stable throughout most of development until 1989 when the Air Force relaxed some of them. Up until that time, though,

Douglas constantly modified the detail requirements and configuration throughout FSED and production in response to problems encountered as the program produced hardware and software.

A design change that had a major impact on the program was the addition of a fly-by-wire electronic flight control system. Douglas officials, with Air Force concurrence, decided in 1987, two years after the start of FSED, that the aircraft needed the electronic system to realize its full capability and meet operational requirements. [Scott, 1991] The change of this magnitude in the middle of FSED, with its attendant systems impacts, contributed significantly to the cost overrun and schedule delays.

Another change with significant consequences was the use of more powerful versions of the engine than used originally. This upgrade was implemented late in development to improve payload capability due to aircraft weight growth. Thrust for each of the four engines increased to 41,700 lb. from the previous rating of 37,000 lb. The resulting increase in exhaust temperature unexpectedly led to the need for a higher-temperature and heavier material for the wing's externally blown flaps, since the old material could not survive the new environment. This added weight and increased cost.

Due to the highly integrated nature of the C-17, Douglas has had to deal with the rippling effect of other design modifications and alterations. Even in 1994 production, the program continues to be adversely affected by issues such as design and materials changes. [PPR, 1994]

Stability has also largely eluded C-17 funding and workforce-levels. The start of FSED was delayed for nearly four years, preventing Douglas from ramping up manpower in preparation. When FSED funding finally came through in late 1985, Douglas had to hire a large number of people in a short period of time. After this, the workforce-level was reasonably stable as Congress supplied funding during the first three years of FSED in accordance with the long term budget plan. In 1989, prompted by slippage in the program schedule, cost increases, and performance problems, Congress started to cut the program's yearly budget and alter the production profile. As a result, Douglas started experiencing constant and increasing labor turnover. This had the effect of severely reducing FSED production personnel in 1992 and 1993, then requiring a sudden ramping up again in 1994.

In addition to cutting funds and reducing production quantities throughout the early 1990s, Congress had threatened to cancel the program altogether. The program was placed on probation at the end of 1993, as part of a settlement between the Department of Defense and McDonnell Douglas. In this settlement, the contractor

was given two years to prove it can meet revised schedule, cost, and specification requirements and successfully complete flight testing. McDonnell Douglas also agreed to spend an additional $456 million on facilities and testing, and drop $1.7 billion in claims against the government. If technical, schedule, and cost performance has improved significanlty by the end of the probation period, the Air Force will be allowed to buy more than the 40 C-17s already delivered or on order. [Lynch, 1994a] If not, Congress will fund off-the-shelf alternatives, such as buying more of the large C-5s or a military version of the 747 cargo freighter. Needless to say, much of the C-17 development and production has been conducted in a volatile political environment with widely varying degrees of support.

Douglas had problems keeping a core C-17 development team together even before the political turmoil. The four-year delay of FSED in the early 1980s prompted some of the key C-17 technical and management personnel involved with the earlier design work to find jobs in other McDonnell Douglas programs that needed the expertise. Stability was also impacted during production in the early 1990s by constant labor turnover due to union seniority rules which gave workers laid off from Douglas' commercial production programs the right to claim jobs on the C-17 line. [Lynch, 1993] Furthermore, in 1989, implementation of the TQMS displaced most workers, and some of the key C-17 personnel did not return. For example, at the executive level,

194 positions were filled in the restructured organization chart, but a year later, fewer than 50 of those executives remained in the same positions. [Smith, 1993b]

The Douglas top-to-bottom TQMS transformation was imposed suddenly and without advance notice. The company's organizational structure composed of functional groupings was virtually eliminated, and the process of defining and filling the new management positions took up to six months to complete. According to some employees, once the positions were filled, many managers were frequently moved from one position to another. Furthermore, some did not have the necessary technical qualifications for the job. [Smith, 1993b]  Unfortunately, this transformation did not achieve its intended effect, and the C-17 program continued to founder.

In 1993, in response to continued technical and management problems, the Department of Defense directed the C-17 SPO and Douglas to implement a new master plan for the C-17 program under the auspices of an Integrated Master Plan. This action established integrated product teams as part of integrated product development (IPD). [SAR, 1993]

If IPD had been adopted earlier in the program it could have enabled the Douglas engineering and manufacturing workers to work better together than they were used to under the traditional

functional organization. Douglas's relationships with subcontractors and suppliers, while businesslike, could also have been enhanced through product teams. As difficulties befell the program, Douglas's interactions with its subcontractors were negatively affected. This was especially true of Honeywell, the avionics developer and integrator, which was replaced in the middle of development.

The Air Force SPO interacted heavily with Douglas, as was required of its oversight role. Traditionally, government program representatives and contractors have had a mildly adversarial relationship. In the case of the C-17, a strongly negative atmosphere pervaded as the many problems became apparent and both sides blamed each other for them, creating gridlock and seriously impeding progress. [Lynch, 1994a] The agreement to relax performance requirements and avert Douglas legal action mentioned previously, in addition to the appointment of a new Douglas program manager who reports directly to the Chairman of McDonnell Douglas, were intended to diffuse the poisonous relations and allow the program to continue.

Throughout development and into production, the C-17 program members depended on the standard means of communication, such as telephones, mail, meetings, and later faxes. Most of the Douglas workers were based in Long Beach, CA., and they were located in buildings within several miles of each other, usually with other

members of their functional specialty. Most of the company's major subcontractors and suppliers have been located across the country, as well as its Air Force customers. Douglas has conducted technical working meetings as well as program reviews and design reviews at a variety of locations to provide the team members the opportunity to work together to develop the aircraft. It has also maintained representatives at subcontractor plants to enhance communication, and some of the subcontractors have representatives at Douglas for the same purpose.

As mentioned earlier, Douglas and the Air Force implemented an advanced computer aided design and manufacturing system at the tail end of FSED in 1994. As an enhancement to team communication, it allowed much quicker transfer of the design to program participants and enhancing the speed and coordination of configuration updates.

Due to the large presence of Air Force representatives and extensive reporting requirements, Douglas's flexibility and autonomy for conducting the C-17 effort was less than what would normally be available on a commercial transport effort. For example, a former Douglas official claimed the management control system imposed by the Air Force required excessively detailed expenditure breakdowns and was expensive to implement. Furthermore, it focused excessively on program detail and led some managers to lose sight of the big picture. [Smith, 1993b]

Also, the Air Force decided to run the test program instead of having Douglas do it as originally planned. This slowed flight test progress down, especially when a three flight per week limitation was imposed. Finally, the large amount of effort required to respond to Air Force and Congressional inquiries diverted the attention of members of the technical and management team from their primary work.

Most of Douglas's workers initially assigned to the C-17 effort were technically qualified for their work. However, as discussed earlier, many engineers, managers, and production floor workers with valuable technical expertise left the C-17 program to take jobs with other companies during the four-year lag between being selected as prime contractor and full development funding. Then, when FSED funding was authorized in December 1985, a sharp surge in commercial aircraft orders, as well as ongoing military programs, made it difficult for Douglas to find employees with required skill levels. [Smith, 1993b] The presence of a large number of inexperienced workers contributed to the production floor inefficiencies.

Douglas is responsible for cost and schedule performance as well as the output of its workers. Furthermore, it is responsible for the performance of the C-17s it delivers to the Air Force. To enforce this accountability, large Department of Defense contracts are required by law to contain warranties providing the

government recourse if the delivered item is inadequate. The C-17 warranty is very extensive and includes provisions to ensure that the C-17s delivered (1) are free from material and workmanship defects at delivery, (2) shall meet or exceed the system level specification reliability, maintainability, and availability requirements, (3) shall have had all subsystems, accessories, equipment, and parts installed according to specification, and (4) shall have airframes that do not develop structural defects. If an item fails to meet any of the above, the contractor must correct the failure at no additional cost to the government. [Warranty Briefing, ca 1994] Given the difficulties experienced on the C-17 program, such assurances are important to the Air Force in establishing confidence in the future viability of the aircraft.

**Summary/Conclusion**

As a large, Air Force-sponsored systems development program, the basic systems engineering fundamentals were attempted to one degree or another during the development of the C-17. However, as previously indicated, some of the activities were not well performed. In addition, the environment in which the systems development was carried out primarily by Douglas was clearly turbulent in many areas, and it significantly contributed to the program's shortcomings. The end results of the C-17's technical and management problems were a significant schedule delay and a

significant cost overrun, but only minimal performance degradation. In spite of the difficult development, the C-17 design is a very capable aircraft and its operational performance is satisfactory to the customer.

Table 3.4-3 C-17 Performance scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| TECHNICAL PERFORMANCE - INITIAL | 0-10 | 1 | 3 | 3 |
| TECHNICAL PERFORMANCE - MATURE | 0-10 | 1 | 9 | 9 |
| COST PERFORMANCE | 0-10 | 1 | 6 | 6 |
| SCHEDULE PERFORMANCE | 0-10 | 1 | 5 | 5 |
| PERFORMANCE TOTAL | | | | 23 |

Table 3.4-4 C-17 Systems Engineering Fundamentals scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| REQUIREMENTS DEVELOPMENT | 0-10 | 2 | 8 | 16 |
| INCIPIENT SYSTEM DESIGN | 0-10 | 2 | 7 | 14 |
| EVALUATING ALTERNATIVE CONCEPTS AND DESIGNS | 0-10 | 1 | 8 | 8 |
| MAKE-OR-BUY DECISION | 0-10 | 1 | 9 | 9 |
| VALIDATION | 0-10 | 1 | 8 | 8 |
| VERIFICATION AND INTEGRATED TESTING | 0-10 | 1 | 8 | 8 |
| CONFIGURATION MANAGEMENT | 0-10 | 1 | 3 | 3 |
| MANUFACTURING CONSIDERATIONS | 0-10 | 1 | 6 | 6 |
| SYSTEMS INTEGRATION AND TECHNICAL MANAGEMENT | 0-10 | 1 | 4 | 4 |
| LIFE CYCLE CONSIDERATIONS | 0-10 | 1 | 8 | 8 |
| PROGRAM MANAGEMENT | 0-10 | 1 | 3 | 3 |
| SYSTEMS ENGINEERING FUNDAMENTALS TOTAL | | | | 87 |

Table 3.4-4 C-17 Development Environment scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| EMPHASIS ON THE CUSTOMER | 0-10 | 1 | 7 | 7 |
| STABILITY OF REQUIREMENTS AND CONFIGURATION | 0-10 | 1 | 2 | 2 |
| FUNDING AND WORKFORCE-LEVEL STABILITY | 0-10 | 1 | 2 | 2 |
| STRONG SUPPORT FOR PROGRAM | 0-10 | 1 | 2 | 2 |
| CONTINUITY OF CORE DEVELOPMENT TEAM | 0-10 | 1 | 2 | 2 |
| STABILITY OF ORGANIZATIONAL STRUCTURE | 0-10 | 1 | 1 | 1 |
| COOPERATION AMONG ALL STAKEHOLDERS | 0-10 | 1 | 3 | 3 |
| EFFECTIVE COMMUNICATION WITHIN TEAM | 0-10 | 1 | 5 | 5 |
| FLEXIBILITY AND AUTONOMY | 0-10 | 1 | 5 | 5 |
| WORKFORCE EXPERTISE AND EXPERIENCE | 0-10 | 1 | 5 | 5 |
| ACCOUNTABILITY FOR SYSTEM PERFORMANCE | 0-10 | 1 | 8 | 8 |
| DEVELOPMENT ENVIRONMENT TOTAL | | | | 42 |

Table 3.4-6 C-17 Design Difficulty scores.

| Elements | Range | Score |
|---|---|---|
| TYPE | 0-15 | 9 |
| KNOWLEDGE COMPLEXITY | 0-10 | 6 |
| STEPS | 0-10 | 9 |
| QUALITY IMPLEMENTATION EFFORT | 0-10 | 6 |
| MANUFACTURING OPERATIONS IMPLEMENTATION EFFORT | 0-5 | 4 |
| SELLING PRICE CONSTRAINT | 0-5 | 2 |
| DESIGN DIFFICULTY TOTAL | 0-55 | 36 |

Table 3.4-7 C-17 Resources scores.

| Elements | Range | Score |
|---|---|---|
| COST | 0-15 | 10 |
| TIME | 0-10 | 8 |
| INFRASTRUCTURE | 0-10 | 8 |
| RESOURCES TOTAL | 0-35 | 26 |

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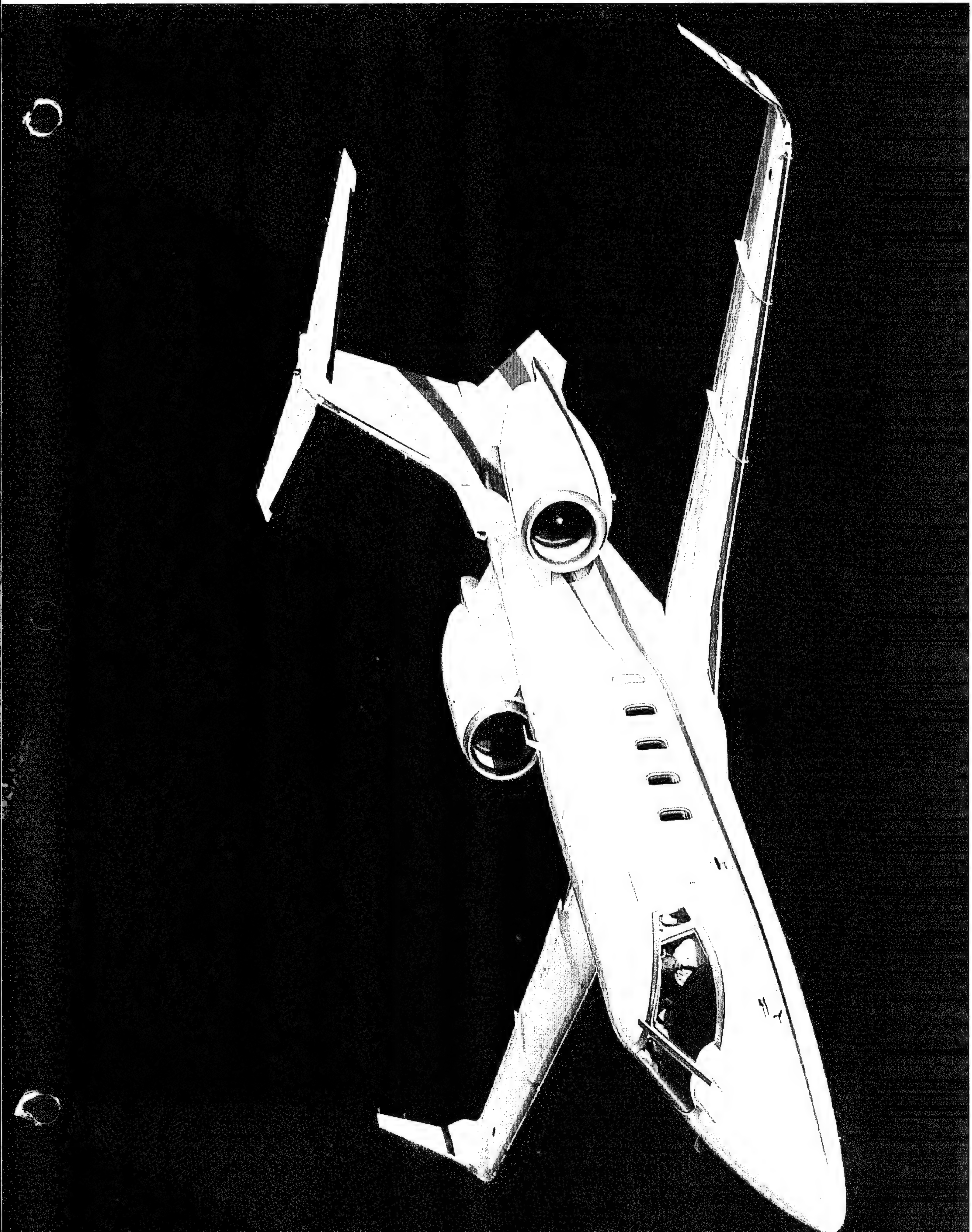


# 3.5 CASE STUDY: LEARJET MODEL 60 BUSINESS JET

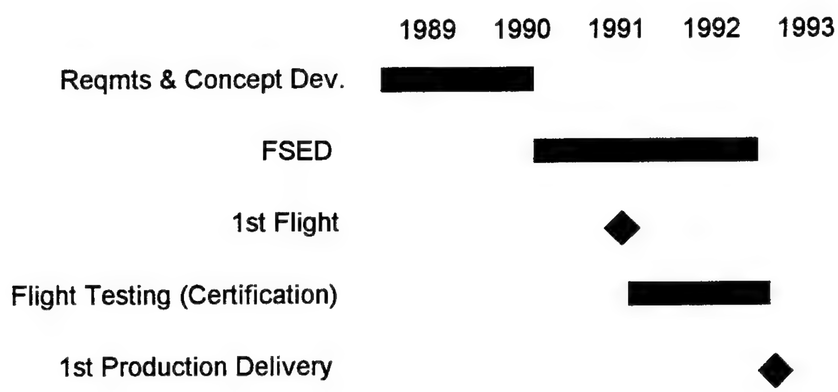
The Model 60 from Learjet, Inc., is a mid-sized, twin-engine, transonic business jet designed for transporting up to eight passengers and luggage on flights of up to 2,750 nautical miles. Learjet developed the Model 60 in response to findings from its marketing research that customers existed for a larger and longer range version of the successful Model 55. Although the company failed to recognize the proper requirements initially, the design group eventually developed an aircraft that met customer desires by carrying out, often informally, many of the fundamentals of systems engineering.

**Development History, Design, and Performance**

Model 60 development began in July 1990. In just a few months, the program moved from concept definition to full-scale engineering development (FSED). The first flight of the engineering prototype took place 11 months later. Development ended in January 1993 with the first delivery of a production unit to a customer. (See Figure 3.5.) This two and a half year development program that included four aircraft was six months behind original schedule (20 percent) and cost about $90 million, which is double its initial estimate for the smaller scope program. The delay and cost growth were due primarily to the requirements changes generated by the marketing department.

However, when considering the cost estimate update after the new requirements were imposed early in FSED, the overrun was about 20 percent. [Etherington, 1994]

Figure 3.5 Model 60 development schedule.




Learjet has been designing and building business jets for about 30 years. The company usually designs and builds the airframe and integrates engines and avionics developed and built by other companies. The Model 60, which is the largest and longest range aircraft Learjet builds, is a direct derivative of the Model 55 that was introduced in 1981. The Model 55 underwent several performance upgrades throughout 1983 and 1984. Then the Model 55B was introduced in 1985 incorporating a digital flight deck and increased takeoff weight. The Model 55C was introduced later, and it incorporated the earlier aerodynamic and performance improvements as well as a few others. The Model 60 retains the Model 55 series enhancements, but adds new elements to the same basic airframe. [North, 1993] The Model 60 development is

classified as a redesign effort.

The primary changes reflected in the Model 60 are more powerful engines, modified aerodynamics, a 3.5 feet fuselage extension, and a larger fuel tank. The results were greater range, improved aerodynamic efficiency, and increased payload.

The Model 60 development program was originally intended to involve merely a 28 inch stretch to the Model 55. [Etherington] Just after the program was initiated, the Federal Aviation Administration (FAA) issued a change in takeoff requirements that required Learjet to use a more powerful engine on the Model 60 than the one used on the Learjet 55. The engine selected, the Garrett-4, was an off-the-shelf design being used on a competing business jet, the Citation 7. The Garrett-4 would easily fit the Model 60 using the existing nacelle and pylon design. Therefore, this was considered a minor change in requirements with only a minimal impact to cost and schedule. [Etherington, 1994]

Several months later, the Model 60 design team presented the preliminary design during the first program review. This meeting was the sales department's first look at plans for the new aircraft. After the presentations, the vice president of the sales department stated that the aircraft would not sell; the design did not match the desires of the customers they had recently surveyed. The sales department then provided new

requirements, primarily increasing range to a transcontinental distance and increasing luggage space. [Etherington, 1994]

These changes had major impacts on the design and the program. The new range requirement drove the need for a more powerful engine, greater fuel capacity, and improved aerodynamic efficiency. To accommodate increased luggage space, the fuselage was stretched about a foot more than the originally planned 28 inches.

Instead of having to convince an engine company to develop a new engine, Learjet engineers found an existing design that met its performance requirements. The PW305 engine from Pratt & Whitney Canada was completing development and was slated for use on the British Aerospace 1000 business jet. Two of the engines could provide 10,450 pounds of thrust, well above the 9,200 pounds of thrust needed. However, to fit on the Model 60, the PW305 required a change in pylon design. [Etherington, 1994]

To implement a new pylon design without increasing drag an unacceptable amount was a greater challenge than expected. [Etherington, 1994] The change also led to modifications to the wing leading edge. Learjet undertook a major effort using the TRANAIR computational fluid dynamics (CFD) code to explore design modification options and using high speed wind tunnel tests to confirm drag predictions. [Phillips, 1991] The new engine also

required the development of full authority digital electronic control software that would optimize power and efficiency electronically and monitor all engine functions.

The integrated avionics suite selected by Learjet was the Collins Pro Line System 4. This system, designed to minimize pilot workload and panel scanning, was essentially off-the-shelf hardware requiring minimal hardware and software modifications.

The Model 60 airframe was designed to last for a time comparable to that found on other business jets. The significant design margin is evidenced by one of the aircraft being subjected to 50,000 continuous cabin pressure cycles of pressures from sea level to 51,000 feet. This is equivalent to 100 years of typical business jet use. [Brochure, ca 1994]

Based on sales projections from its sales department, Learjet established its production tooling requirements for 150 units. By the first delivery in January 1993, Learjet had 33 firm orders (about a one and a half year backlog) and was expecting to be producing Model 60s at a rate of 18-33 units per year to at least the year 2000 if projected sales materialized. As of July 1994, Learjet had sold about fifty Model 60 aircraft. The unit production sales price of one of the aircraft in mid-1994 was approximately $9.5 million. [Etherington, 1994]

The Model 60 development was a company funded effort performed by a small team of Learjet employees located at the company's Wichita, Kansas, headquarters. About 200 people, including subcontractors, were involved in the design and prototype fabrication, and they used many of the design, analysis, and manufacturing tools used by the aerospace industry in the late 1980s and early 1990s.

**System Engineering Fundamentals**

In the development of the Model 60, the Learjet team followed many of the fundamental systems engineering principles and techniques. However, much of the process was conducted with minimal formality. Given the relatively low complexity of this redesign effort, such an informal approach was adequate and appropriate.

Some formality in the development process was evident in certain controlled documents. Specifically, the design requirements were documented in a system specification by the engineering department after receiving the top level customer desires from the marketing department. The other formal documents consisted primarily of a test master plan, test plans and procedures, a configuration management plan, and a quality plan. Interface control documents were also maintained and controlled. However, no systems engineering management plan or equivalent was

developed by Learjet, and neither were subsystem specifications. Subsystem specifications probably existed with the subcontractors who had developed their items independently of Learjet, but they were not generated as part of the Model 60 development.

Given the redesign nature of the development effort and the minimal complexity, the Learjet team did not formulate a new top level model of the aircraft and its subsystems, nor did it establish a work breakdown structure. However, it did allocate requirements and define new interfaces as a result of the performance requirements and subsystems that were different than those of the Learjet Model 55C. [Etherington, 1994]

Other systems engineering tasks of the design process were also somewhat informal. While modeling and analysis tools were used to assess and refine the design, primarily in the area of aerodynamics, the team never performed a formal tradeoff analysis of options. Nor was a risk analysis performed. [Etherington, 1994] Instead of beginning from a clean slate, the existing Model 55C was deemed the starting point of development with the expectation that the end result would be merely a modification. The approaches to meet the performance requirements, with the possible exception of the aerodynamic refinements, were rather straight forward given the initial design constraints.

Consistent with its stated company approach, Learjet built the

Model 60 airframe in-house and obtained most of the subsystems from elsewhere. This is reasonable since Learjet is not a large aerospace company, and it does not possess the resources in people, facilities, and experience to fabricate everything itself in an economical manner. On this fact alone, Learjet would be expected to conduct no more than minimal make-or-buy evaluations since the make-or-buy decisions were clear cut on most items. Furthermore, since the Model 60 uses a majority of the same subsystems and components as the Model 55, most of the parts and suppliers were already set. Despite only limited evaluations, the Model 60 make-or-by decision performance based on Learjet's policy was reasonable.

Since the Model 60 is a direct redesign, there was not a significant issue in the beginning with regards to being able to technically develop it. The program, however, never performed a validation audit of its requirements. [Etherington, 1994] Instead, Learjet appears to have relied primarily on the market surveys early in the program that indicated that potential customers were interested in increased range and payload. The Model 60 team also performed extensive simulation testing and analysis to validate the aerodynamics requirements of the aircraft.

Learjet followed verification and integrated testing in a manner required for FAA certification. Therefore, most of the

verification and integrated testing requirements were known at the beginning of the effort. The program created and flew one engineering prototype before completing three deliverable preproduction units that were flown in the flight certification test program. Based partly on the results of the engineering prototype flight test, additional refinements were made to the design to improve range, handling, and center of gravity limits. [Aviation Week, 1991] These changes were retrofitted into the engineering prototype and incorporated into the four preproduction prototype aircraft. No major problems hampered the completion of development from that point to production, and no major manufacturing or quality problems developed. The only issue of note was the need for minor modifications to the environmental control system. Aside from the varying options ordered by different customers, the basic aircraft configuration has remained highly stable from the four preproduction prototypes through production. [Etherington, 1994] Furthermore, the four preproduction units were delivered to customers after the successful completion of the 18-month flight test program and FAA certification.

The off-the-shelf integrated avionics suite simplified the integration task for Learjet by reducing the interfaces Learjet had to develop. The avionics supplier, Collins, was responsible to Learjet for ensuring that the flight management system computer, the navigation and guidance units, the weather radar,

and the cockpit displays all worked together when installed in the airframe. Purchasing the entire avionics suite from one source reduced the need for extensive ground avionics integration testing by Learjet. Also, with the engine already having been developed and flight tested by Pratt & Whitney Canada on a different test aircraft, the first engines arrived at Learjet as developed and tested units. Therefore, Learjet's developmental testing responsibility was primarily system-level using engineering and production prototype flight units to demonstrate integrated performance as part of FAA certification requirements.

The changes in requirements, interfaces, and configuration that occurred throughout FSED were all controlled adequately by Learjet. While the program did not have a full-blown configuration management system, it did have a formal change control system with a change control board. [Etherington, 1994]

Since Learjet is a small, manufacturing oriented company, the production organization was involved early in the program to help in planning for production. Since the Learjet was a redesign of a successful aircraft, there was not a strong motivation to review and possibly revise the manufacturing processes for the Model 60 to improve ease of manufacturing and reduce cost. Learjet, however, used some computer aided design (CAD) partially integrated with advanced numerically controlled milling machine tools for manufacturing airframe components. The fabrication of

the Model 60 did not, however, require the development of advanced, unique manufacturing processes.

Even though Learjet was not involved in developing the avionics suite and propulsion units, the Model 60 team had to manage the avionics integration into the airframe, as well as the interfaces between the engines and airframe. The most critical interfaces between subsystems that Learjet had to directly control were those between the avionics and the engines. This was done with extensive involvement by the engine and avionics subcontractors.

The management of the systems integration as well as the entire technical effort was done in a manner consistent with a small, cohesive technical team. Consequently, the only formal reviews held were the preliminary design review and software walk-throughs on the digital engine control software. These were in addition to the weekly engineering meetings involving primarily Learjet team members. There were limited forums for formal review of the design, but they do not appear to have been needed since the customers were not involved in development.

Life cycle considerations did not require a major amount of attention from the design team. The ground support equipment, maintenance procedures, and the training were the same as for the Model 55, with the exception of support elements dealing with the new engine. Furthermore, the Learjet design team appears to have

sought to maintain mission reliability at the level of the Model 55, already very high, rather than to push for marginal improvements. However, the Model 60 does incorporate a key supportability feature to enhance maintenance operations, which is a built-in diagnostic system in the engines to record performance data.

In order to plan and track the progress of the Model 60 development effort, the program manager used Gantt chart scheduling and a computerized cost accounting system. While not particularly sophisticated tools, they were adequate for the relatively low complexity level of the effort. The program manager, however, did not convene regular program reviews, which was indicative of the informal nature of conducting the development.

**Development Environment**

After the requirements changes early in FSED, the development environment was stable due to consistent funding, stable requirements, low personnel turnover, and reasonably high configuration stability. The Model 60 development was fully funded by Learjet and FSED was initiated even before firm orders were received. The company funded the effort at a rate of about $30 million per year. Learjet had made a strong commitment to develop the aircraft and did not constrain funding flow, reduce

the workforce, or threaten to cancel the effort as the cost estimates increased due to the changes in scope.

Designers used a 3-dimensional wire-frame computer aided design (CAD) program called UG II for designing the portions of the Model 60 that were different from the Model 55. In addition to the use of a CFD program with a NASA Cray computer and wind tunnels to verify CFD results as mentioned previously, the design team utilized the NASTRAN finite element program for mechanical analysis and AutoCAD for minor wiring diagram changes. A cabin mockup was built to show cabin modifications, and one engineering prototype flight unit was fabricated and flown.

The Model 60 was developed in a close-knit project team environment. The relatively small airframe and integration engineering team was physically located together, and the manufacturing personnel were on the same grounds. Close cooperation existed between the Learjet personnel and those from the major subcontractors. However, Learjet did not oversee the development of the major subsystems, especially since they were already developed by the time the program began. Neither did the development team have any direct involvement with the customers, most of whom were corporations. That task was left to the sales department, and it appears that interaction between the top-level requirements developers and the design team was limited.

The limited complexity of the program, the small size of the development team, and the physical proximity of the Learjet members with each other enabled adequate communication within the technical team, thereby precluding the need for more formal systems engineering activities and techniques. Furthermore, the maturity of the major subsystems lessened the degree of Learjet's oversight activities over the subcontractors and minimized potential communication problems.

The Model 60 was designed to attain specific performance on a variety of parameters, the primary one being range. The warranty, however, does not address it or other performance parameters specifically. Instead, the warranty covers the failure of parts built by Learjet that occur within five years after delivery and the failure of parts manufactured by subcontractors and vendors that occur within two years after delivery.

**Summary/Conclusion**

The Model 60 aircraft design attained the range and capacity performance desired by the business jet market and specified by the Learjet sales department. In achieving this success, the development team performed many of the fundamental practices of systems engineering in an informal manner on this primarily low-risk redesign effort. While the development environment was reasonably stable in most areas, the requirements development

process in the beginning of the program was not conducted effectively. The consequences of the changes in key requirements after program initiation were increased scope, delay in schedule, and cost overrun. Despite these shortcomings of the development effort, the Model 60 met its key performance requirements and satisfied its customers.

Table 3.5-1 Model 60 Performance scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| TECHNICAL PERFORMANCE - INITIAL | 0-10 | 1 | 9 | 9 |
| TECHNICAL PERFORMANCE - MATURE | 0-10 | 1 | 10 | 10 |
| COST PERFORMANCE | 0-10 | 1 | 2 | 2 |
| SCHEDULE PERFORMANCE | 0-10 | 1 | 4 | 4 |
| PERFORMANCE TOTAL | | | | 25 |

Table 3.5-2 Model 60 Systems Engineering Fundamentals scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| REQUIREMENTS DEVELOPMENT | 0-10 | 2 | 1 | 2 |
| INCIPIENT SYSTEM DESIGN | 0-10 | 2 | 7 | 14 |
| EVALUATING ALTERNATIVE CONCEPTS AND DESIGNS | 0-10 | 1 | 6 | 6 |
| MAKE-OR-BUY DECISION | 0-10 | 1 | 8 | 8 |
| VALIDATION | 0-10 | 1 | 5 | 5 |
| VERIFICATION AND INTEGRATED TESTING | 0-10 | 1 | 8 | 8 |
| CONFIGURATION MANAGEMENT | 0-10 | 1 | 7 | 7 |
| MANUFACTURING CONSIDERATIONS | 0-10 | 1 | 5 | 5 |
| SYSTEMS INTEGRATION AND TECHNICAL MANAGEMENT | 0-10 | 1 | 7 | 7 |
| LIFE CYCLE CONSIDERATIONS | 0-10 | 1 | 7 | 7 |
| PROGRAM MANAGEMENT | 0-10 | 1 | 6 | 6 |
| SYSTEMS ENGINEERING FUNDAMENTALS TOTAL | | | | 75 |

Table 3.5-3 Model 60 Development Environment scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| EMPHASIS ON THE CUSTOMER | 0-10 | 1 | 6 | 6 |
| STABILITY OF REQUIREMENTS AND CONFIGURATION | 0-10 | 1 | 3 | 3 |
| FUNDING AND WORKFORCE-LEVEL STABILITY | 0-10 | 1 | 8 | 8 |
| STRONG SUPPORT FOR PROGRAM | 0-10 | 1 | 8 | 8 |
| CONTINUITY OF CORE DEVELOPMENT TEAM | 0-10 | 1 | 10 | 10 |
| STABILITY OF ORGANIZATIONAL STRUCTURE | 0-10 | 1 | 9 | 9 |
| COOPERATION AMONG ALL STAKEHOLDERS | 0-10 | 1 | 8 | 8 |
| EFFECTIVE COMMUNICATION WITHIN TEAM | 0-10 | 1 | 5 | 5 |
| FLEXIBILITY AND AUTONOMY | 0-10 | 1 | 8 | 8 |
| WORKFORCE EXPERTISE AND EXPERIENCE | 0-10 | 1 | 8 | 8 |
| ACCOUNTABILITY FOR SYSTEM PERFORMANCE | 0-10 | 1 | 6 | 6 |
| DEVELOPMENT ENVIRONMENT TOTAL | | | | 79 |

Table 3.5-4 Model 60 Design Difficulty scores

| Elements | Range | Score |
|---|---|---|
| TYPE | 0-15 | 3 |
| KNOWLEDGE COMPLEXITY | 0-10 | 4 |
| STEPS | 0-10 | 6 |
| QUALITY IMPLEMENTATION EFFORT | 0-10 | 5 |
| MANUFACTURING OPERATIONS IMPLEMENTATION EFFORT | 0-5 | 3 |
| SELLING PRICE CONSTRAINT | 0-5 | 4 |
| DESIGN DIFFICULTY TOTAL | 0-55 | 25 |

Table 3.5-5 Model 60 Resources scores.

| Elements | Range | Score |
|---|---|---|
| COST | 0-15 | 9 |
| TIME | 0-10 | 5 |
| INFRASTRUCTURE | 0-10 | 6 |
| RESOURCES TOTAL | 0-35 | 20 |

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MD-11
MCDONNELL DOUGLAS
11
MD-11
TECHNOLOGY FOR THE 21ST CENTURY
MCDONNELL DOUGLAS

## 3.6 CASE STUDY: MCDONNELL DOUGLAS MD-11 COMMERCIAL TRANSPORT

The MD-11 is a large, long-range, three-engine commercial transport developed in the late 1980s and early 1990s by the Douglas Aircraft Company of the McDonnell Douglas Corporation for commercial passenger and cargo travel. The MD-11 was intended to fit into a market segment between the large capacity Boeing 747 and the medium capacity Boeing 767 and Airbus Industrie A300 and A330. The MD-11's direct competitors are the four-engine Airbus A340 and the new twin-engine Boeing 777. Douglas initially approached the MD-11 development as a relatively simple, low risk modification of the DC-10. The effort, however, quickly became significantly more complicated as unanticipated systems issues appeared. As a consequence, the program was a difficult experience. However, despite problems during development and initial customer operation, the MD-11 was eventually developed into a successful product.

### Development History, Design, and Performance

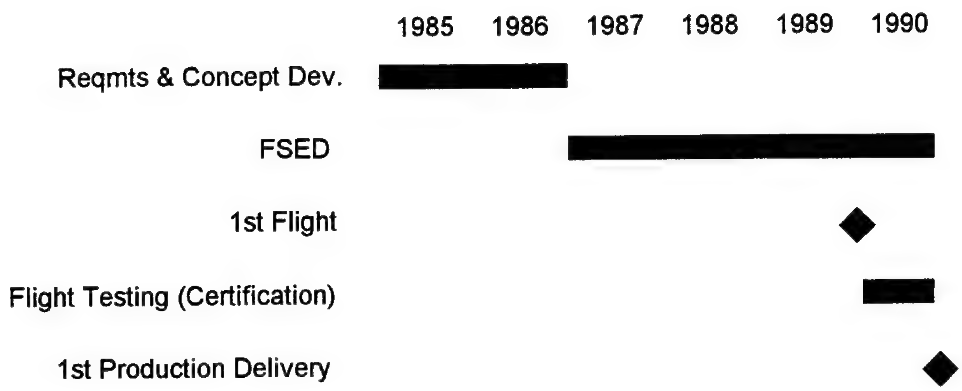
McDonell Douglas launched the MD-11 full-scale engineering development and production (FSED) program on December 30, 1986, with firm orders from twelve airlines for 52 aircraft and options for 40 more. The first flight took place three years later on 10 January 1990. The flight test program involved five aircraft for ten months, allowing the first customer delivery in late 1990.

(See Figure 3.6.) Up until flight testing, the development program was nearly a year behind original schedule due to a variety of problems at Douglas. These included overly optimistic schedules, delays in receiving parts, sweeping management and production changes attempted in the middle of development, and various technical difficulties. [Aviation Week, 1989] However, the company reduced the schedule delay during flight testing, and the first customer delivery of a certified aircraft was nine months (23 percent) late.

The $722 million development effort was funded entirely by McDonnell Douglas, and it experienced an overrun of about 30 percent over the original baseline cost. [Larson, 1995] By late 1994, 122 MD-11s had been delivered, 51 units were in various stages of fabrication, and 88 were on option or reserve order. This is in excess of the program's break even point for MD-11 deliveries, thereby making the MD-11 a profitable venture. [Larson, 1995] The 1994 selling price for each of the initial, shorter range versions of the MD-11 with standard training and maintenance manuals is about $116 million.

The MD-11 is a stretched and updated version of the DC-10, and it therefore can be categorized as a redesign. The initial version was designed to carry nearly 300 passengers a distance of almost 7,000 miles. The basic airframe is the same as the DC-10, but the fuselage is 18 feet 6 inches longer, aerodynamics

Figure 3.6 MD-11 development schedule.




are improved, more powerful engines are used, and a new highly integrated digital avionics system is incorporated. The MD-11 design philosophy was to use a high level of automation to take care of routine flying tasks as well as emergency procedures automatically, thereby enabling two pilots to handle the workload without a flight engineer. As a consequence, the cockpit has sixty percent fewer switches, gauges, and lights than the DC-10. [Aviation Week, 1990a]

The fact that the MD-11 was a derivative, or redesign, of the DC-10 helped reduce development risk. However, major technical challenges still existed that Douglas did not anticipate. Of primary significance was the sophisticated new digital avionics system which impacted every subsystem on the aircraft. [Smith, 1990b] This dual flight management system allows automatic operation of the aircraft fuel, air, electrical, and hydraulic systems, and it also incorporates the automatic flight system.

Each of these subsystems is controlled by a pair of dedicated computers. The subcontractor Honeywell was responsible for supplying and integrating all the avionics for the program, a role normally filled by the aircraft contractor. Even though Douglas personnel oversaw the complex avionics integration effort instead of performing it, Douglas still had to integrate the avionics with the rest of the aircraft. This required developing new interface devices for the analog DC-10 components that were carried over into the MD-11 design as well as for new subsystems. From Douglas' point of view, its avionics challenge was therefore mainly that of software integration, since that was the major area with which they had little knowledge or experience. [Smith, 1990b] The software problems turned out to be more difficult to deal with than expected.

The MD-11 development team also faced a significant challenge to improve aerodynamic performance. The design target was to reduce drag by eight percent compared with the DC-10. [Aviation Week, 1990b] To achieve this, the designers included improved aerodynamic features such as winglets, a redesigned wing trailing edge, a smaller horizontal tail with integral fuel tanks, and an extended tail cone. A considerable amount of wind tunnel testing was conducted to verify and refine the design. At the time of the first aircraft deliveries, drag reduction was short of the goal. Nominal aerodynamic performance, however, was reached in 1991 and retrofitted into completed aircraft.

While Douglas anticipated some difficulties with improving aerodynamic design, it didn't expect many hardware problems. One such problem that did arise impacted key performance. The fuel consumption performance for the engines from Pratt & Whitney and General Electric, both which are upgraded versions of established propulsion units used on other aircraft, were below design requirements by amounts from 4.5-6 percent for the initial units delivered to Douglas. [Smith, 1990c] Although the engine subcontractors improved fuel consumption efficiency throughout development and production, the original allocated performance goal was never achieved. [Larson, 1995]

Compounding the engine shortfalls was another problem common to most aircraft programs, weight growth. The earliest MD-11s were about 4,000 lb., or one and a half percent, above projected empty weight. The extra weight was a result of changes in preliminary load figures, higher than expected weights for the interior configuration, some new MD-11 components from subcontractors, and configuration changes requested by customers. [Smith, 1990b] The result of the overweight condition coupled with the lower engine efficiencies and the less than expected improvements to aerodynamics was that the initial MD-11s did not meet the promised payload/range performance. This was of critical importance since many of the customers were drawn to the advertised MD-11 payload/range capability which enabled them to fly profitable non-stop international flights. Furthermore,

Douglas was contractually liable for payload/range capacity. Although Douglas eventually resolved most of the shortfall primarily through aerodynamic improvements and weight reductions, the initial aircraft delivered were not in compliance and had to be modified once fixes were identified. At four years into production, the MD-11s coming off the production line are meeting all performance guarantees. [Larson, 1995]

Given the high level of commonality between the MD-11 and the DC-10 and the fact that the DC-10 production line was ending at the same time the MD-11 fabrication was to begin, manufacturing planned to refurbish most of the DC-10 tooling to original condition for MD-11 use. The rest of the needed tooling, about twenty percent of the total, were either modifications or new purchases. [Aviation Week, 1987]

With the commonality between the MD-11 and DC-10 designs and production lines, it is not surprising that the MD-11 experienced the same type of manufacturing problems, primarily inefficiency on the production floor. This situation was indicated by a high degree of rework and repair and was due to quality related problems. Another measure of inefficiency is the percentage of drawing rereleases from the initial drawings for an aircraft on the production floor. These drawing changes are a result of design updates due to errors as well as customization features requested by the customer, and a 40 percent rate was not uncommon

at Douglas. Such errors are expensive. The administrative cost of processing these drawing rereleases, or engineering orders, is about $4000 per drawing, and the initial MD-11s built had from approximately 100 to 350 engineering orders against each. [Larson, 1995]

In order to improve the way it did business and reduce manufacturing costs, McDonnell Douglas tried to implement a product teaming approach which it called the Total Quality Management System (TQMS) throughout the entire corporation in 1989, including Douglas. This effort restructured Douglas's entire way of developing aircraft, thereby replacing the traditional functional and hierarchical management approach. This transformation, however, was not carried out effectively. Furthermore, anticipated improvements have not yet become tangible as high error rates are still seen on the newest MD-11s coming off the production line. [Larson, 1995]

While the MD-11 design has its problems, it does possess a certain flexibility and robustness. From the outset of the program, there were four versions of the MD-11 planned. These consisted of the standard MD-11, the longer range MD-11ER with a standard DC-10 length fuselage, the MD-11 combination passenger/ freight transport, and the MD-11F all-cargo aircraft. Later, a stretched version of the MD-11, the MD-12X, was also considered. And finally, Douglas is looking at a possible twin-engine version

of the MD-11.

This flexibility is due partly to the structural margin included in the basic airframe design. Douglas Aircraft Company airplanes have the best structural integrity of the large airliners. [Larson, 1995] They have traditionally been overdesigned for safety reasons as part of a conservative design approach. The company, therefore, has not been inclined to embrace new, lightweight structural materials as much as it competitors. For example, the MD-11 has a somewhat low overall composite content by weight of 3.7 percent compared to about 9 percent for the Boeing 777. The added structural weight contributes to longer airframe life. The projected design life of the MD-11 airframe is 60,000 flight hours, or 20,000 flights. (Airplane wear is a function of cycles, not flight time.) The aircraft can fly for longer periods, but Federal Aviation Administration (FAA) requires more inspections after 60,000 hours. Having greater structural integrity can extend useful operating life beyond the projected life, and this makes a Douglas airplane design better for modification and re-engining. As a result of this structural robustness, Douglas aircraft generally have greater resale value than its competitors. [Larson, 1995]

While airlines and air freight carriers may consider long term design flexibility and resale value as an element in customer satisfaction, operating performance is the fundamental

determinant. One example of this deals with the MD-11's controllability. According to a Douglas engineering manager, the DC-10 has a reputation for being an excellent pilot's airplane. [Larson] Therefore, the MD-11's controllability was judged against the DC-10. The FAA and Douglas pilots who flew the MD-11 during certification flights agree that the aircraft's handling qualities and control harmony are equal to or better than those of the DC-10. [Scott, 1990]

While payload/range performance has always been superior to the DC-10, the initial MD-11s were not meeting the requirement. Over a period of two years, Douglas developed improvements and had them retrofit into the delivered aircraft. In the meantime, though, the airlines had less capable aircraft to operate.

The performance of the initial MD-11s was marginal in other areas as well. One example deals with the experience by one of the first MD-11 customers, Swissair. The airline experienced numerous minor, but frequent and annoying mechanical problems during the initial months of operation involving the fuel system and passenger comfort and entertainment systems. In spite of the many problems, Swissair claims it experienced fewer overall early phase-in problems with the MD-11 than for other aircraft for which it was an initial, or launch, customer. [Lenorovitz, 1991]

American Airlines, another early customer, was greatly displeased with the MD-11's initial performance. Like Swissair, American had to undergo a difficult period of aircraft introduction. After Douglas spent a considerable amount of resources correcting problems, the airline became satisfied with the MD-11. Now that the primary problems have been worked out by Douglas, the aircraft in operation and those coming off the production line exceed stated performance requirements in almost all categories. [Larson, 1995]

The MD-11 has a total of 434,970 parts, not including nuts and bolts. With a system this large and complex, some problems can be expected for the first units regardless of how well the development is carried out. However, most of the MD-11 problems could have been prevented had Douglas not underestimated the integration challenge.

**Systems Engineering Fundamentals**

Over the past thirty years, Douglas Aircraft Company, which is one of the world's largest developers and manufacturers of commercial passenger jet aircraft, has produced a series of successful commercial transports, including the DC-8, DC-9, DC-10, and MD-80. During this time, it had developed its own version of a traditional approach to aircraft development. It was essentially a sequential process by which engineers drove the

aircraft design with minimal influence by non-engineering organizations. Manufacturing was involved during the design phase in order to plan for fabrication, but it was not in a role to significantly influence the design itself. Furthermore, the Douglas approach was further identified by a breakout of the technical and non-technical specialties under separate and highly functionally oriented organizations. This approach, with its attendant weaknesses, was in place at the beginning of the MD-11 development effort.

During the development of the MD-11, the company possessed aerospace and systems development tools standard for the mid-1980s, such as computer aided design and drafting, mechanical analysis programs, computer simulations, and wind tunnels. It was therefore adequately equipped to conduct a redesign effort.

The primary market potential for the MD-11 was as a replacement for the DC-10s and Lockheed L-1011s flying transcontinental and international routes. Since top McDonnell Douglas and Douglas Aircraft Company management viewed the MD-11 as a relatively straightforward modification of an existing design, there was little emphasis on developing a new set of system requirements. As a result, no integrated requirements document was developed at the beginning of the program. Instead, Douglas used the existing DC-10 specification and the standard commercial aircraft design specification, DS-1100. [Larson, 1995] Douglas's approach to

supplementing these old requirements documents was to use marketing surveys to refine higher level requirements. However, concerning detail design issues, the development team made assumptions as to what the airlines would want. [Larson, 1995] There was one exception. Douglas involved pilots from thirty-seven airlines in the development of the MD-11 cockpit.

The detail requirements, although incompletely defined by the MD-11 designers and inadequately flowed down to lower-tier suppliers, were allocated to closely match DC-10 system model. Furthermore, while many of the subsystems did not change much, the interfaces between many of them did. This was due in large part to the new integrated avionics system that tied together many of the aircraft's functions.

Douglas had delegated integrated avionics development responsibilities to its subcontractor, Honeywell, and the engine development was the responsibility of Pratt & Whitney and General Electric. Furthermore, the company sought to maintain a high degree of design and manufacturing process commonality with the DC-10 in order to reduce the MD-11 development risks and costs. Nevertheless, alternative subsystems in areas directly under Douglas's design control were considered to a limited extent throughout the aircraft. Two of the key areas where Douglas performed considerable tradeoff analysis were aerodynamics and structural weight, both in order to improve fuel efficiency and

achieve the payload/range performance requirements.

Analysis had also gone into determining whether to develop and build a subsystem or component in-house, or buy it from outside the company. There are, however, several major components that Douglas does not even consider fabricating itself. Its role is primarily that of airframe manufacturer and integrator, and therefore it purchases engines and avionics from companies specialized in those areas. Regarding the airframe and the rest of the aircraft, the large number of subcontractors and suppliers, both national and international, attest to a high level of consideration going into the make-or-buy decision process.

Validating the MD-11 requirements was another activity performed by Douglas, though not necessarily in a formal manner. Since the MD-11 was a redesign that did not require the development of new technologies, it was obvious to Douglas that the system could be built. Furthermore, through the use of computer simulations and wind tunnel testing, Douglas was confident that the aircraft it was designing would meet the customers' top-level requirements as understood from the marketing surveys and discussions with the airlines that had placed firm orders. However, it did not accomplish formal requirements audits.

As systems integrator with a large number of subcontractors and

suppliers, Douglas was focused more on verifying performance at the system-level rather than at the component and subsystem-level. However, during FSED, it participated and paid close attention to the tests performed by subcontractors. This was especially true for the engine tests.

In-house, Douglas used a variety of tools to assist in verification activities. It built and tested wind tunnel models to refine the aerodynamic design. A DC-10 fuselage was turned into a MD-11 development mockup, and it was used for checking mechanical fit of interior components and potential cabin configurations. No engineering prototypes were built, though. The first units produced were relatively mature configurations, and they were subjected to a full range of inspections and tests. Furthermore, they were delivered to customers after modifications at the end of flight testing.

Although avionics integration was performed primarily by the subcontractor Honeywell, Douglas representatives participated in and conducted some of the testing. Due to the critical importance of the avionics to the entire aircraft, a large amount of avionics ground testing and software checks had been planned. Some of these tests were performed on a flight deck simulator that was run by actual aircraft computers. These activities were accomplished well in advance of the first flight test, with some of them in the Douglas avionics test center.

Although considerable ground avionics component checkout by Douglas occurred during development, the production verification approach was very different. During production, Douglas installed avionics units without bench testing and returned any faulty ones to the manufacturer. This placed the avionics component verification burden on Honeywell, and it allowed Douglas to eliminate its avionics test center. [Aviation Week, 1987]

The MD-11 was subjected to a comprehensive series of integrated flight tests in accordance with a comprehensive test and evaluation master plan leading to certification by the FAA. In preparation of testing, 350 miles of test wiring and more than 1000 remote sensors were installed during assembly of the first aircraft so that 8,000 different temperature, pressure, acceleration, and stress measurements could be recorded. [Kubel, 1991] When completed, this MD-11 was subjected to ground vibration tests to demonstrate that the airframe had sufficient structural damping characteristics. It passed with no problems.

Five of the first production MD-11s were used for FAA flight certification testing. While originally planning for only three aircraft, Douglas added two more to minimize a slip in the overall program schedule. Two of the units were focused mainly on avionics testing, while the other three were primarily dedicated to aerodynamic, engine, functional and reliability testing.

Douglas performed interface and design configuration status accounting and control with varying degrees of success. Most of the initial MD-11 design was placed on two-dimensional computer aided design and drafting (CAD-D) tools, and much of it was transferred directly from the DC-10 paper drawings. Three dimensional wireframe CAD-D was employed on about 40 percent of the configuration, but it was used primarily to assist in making the two-dimensional drawings. To control changes to the design configuration and interfaces, Douglas had an administrative system of review, approval, and implementation.

Despite residing in a computer system, the functional drawings were not integrated. With separate mechanical, electrical, structural, and fuel drawings for the same area, and different sets of people responsible for these different drawings, and these different sets of people in most cases reporting to different managers, the act of effectively assessing the impacts of changes was difficult. As a result of this arrangement and the integrated avionics system interfacing with most of the aircraft's subsystems, there were many interface problems. [Larson, 1995]

Despite the shortcomings of the tools and methods for identifying interface problems and controlling changes, such issues were eventually resolved. To assist in the process, Douglas developed an order of precedence for interface dispute resolution. The

areas of most importance to least importance on a priority scale were (1) pilot control, (2) fuel system, (3) environmental ducts, (4) electrical system, and (5) interiors/insulation blankets. [Larson, 1995]

The interdisciplinary nature of a complex system like the MD-11 suggests an early design involvement by a variety of specialties along with engineering. Perhaps foremost of these specialties is manufacturing. However, early manufacturing involvement did not occur to the extent it should have. As a redesign effort, Douglas did not intend to significantly change manufacturing processes for the MD-11. Furthermore, as mentioned earlier, a majority of the MD-11 manufacturing tooling and processes were taken directly from the DC-10 production line with the assumption that this would keep the up front program costs low. Therefore, there were no pressures placed on engineering and manufacturing personnel to redesign parts for the purpose of lowering production cost.

As the MD-11 weight problems and cost overrun became apparent in the middle of development, Douglas began to implement producibility efforts involving manufacturing that have been continued into production. These efforts, called design for manufacturing and assembly (DFMA), were focused on weight reduction, production cost reductions through the simplification of parts, and production cost reductions through the change of assembly order. This push to reduce manufacturing costs was also

driven by competitive pressures to reduce the sales price of the MD-11. [Larson, 1995]

During MD-11 development, there was no systems engineering management plan or equivalent, nor has there been a separate systems engineering group. In the original organization, the engineering design department was responsible for systems engineering. The MD-11 chief design engineer, who was also the program manager, was head of this department. He worked with the heads of the functional engineering specialties in the engineering organization under him, and he had a staff of deputies that he individually assigned to work technical problems. The deputies were responsible for identifying and bringing issues to the chief design engineer for resolution. However, these issue oriented engineers did not have formal authority over the non-engineering technical specialists, the subcontractors, or even some of the engineers. Furthermore, there was a tendency on the part of the deputies of not wanting to escalate issues since they wanted to try and resolve them themselves. [Larson, 1995] This behavior prevented issues from being communicated adequately throughout the team and resolved in a more timely manner.

In addition to the deputy design engineers, an independent team, called the system compliance engineering group, was chartered to roam throughout the program, find issues, and help fix them. The

problem with this overall arrangement was that nobody was clearly in charge of interdisciplinary issues except the chief design engineer. The lower-level responsibilities were separated primarily by functional specialty, and nobody was responsible for the cross-functional activities of a specific area of the aircraft. This situation contributed to the interface difficulties of the program.

Major subcontractors played critical, and sometime leading, roles in MD-11 development. While the key subcontractors had on-site representatives at Douglas, their technical work was done back at their facilities. Furthermore, since Douglas had no permanent, on-site technical personnel at the subcontractors' locations, they were on the road a considerable amount of time visiting the subcontractor plants.

The delegation of critical responsibilities to subcontractors freed Douglas of some work, but resulted in difficulties in addition to large amounts of travel. Since too many details were vague or not specified in the specifications and subcontracts, Douglas had only limited control over what activities it could get the subcontractors to perform. This became more of an issue as the design changed and the schedule slipped due to the underestimation of the development effort by Douglas. While relations between Douglas and its subcontractors can be considered normal overall, some scope of work conflicts did

result in legal action and delays. Because of this, a Douglas engineering manager believes Douglas should have done more in-house integration. [Larson, 1995] Despite the difficulties, Douglas eventually succeeded in integrating the subsystems and the airframe.

Recognizing the problems inherent in the functionally oriented way the entire corporation did business, McDonnell Douglas tried to implement the TQMS mentioned earlier. The MD-11 organization was part of this transformation, and it occurred in the middle of the aircraft's development. This attempt was painful to the company due to its poor execution. The change took much longer to implement than planned, and the disruption contributed to the slip in schedule. The MD-11 effort, however, did eventually move into a more product oriented structure with interdisciplinary product team members physically located together. By the time this structure was fully implemented and functioning, development was complete.

According to a Douglas engineering manager, a crossfunctional teaming arrangement like integrated product teams would have helped MD-11 development if it had been in place at the beginning of the program. [Larson, 1995] Such a structure would have improved the efficiency of technical management and systems integration.

Despite technical management problems, life cycle issues were addressed by the MD-11 development team throughout development. These issues included reliability, maintainability, and training. Such supportability issues, though, were not a major challenge. The aircraft was designed to be fully compatible with existing ground support equipment and to require about the same level of maintenance as the DC-10. [Lenorovitz, 1991] Training was also very similar. Additionally, the detailed approach to achieve the DC-10-level safety related reliability goals was contained in a reliability plan, and it was verified by flight testing. Therefore, operating costs were projected to be as good if not better than the DC-10.

Life cycle issues, like all other MD-11 issues, were ultimately the responsibility of the program manager. As mentioned earlier, the program manager also filled the role of chief design engineer, and he was given full responsibility to execute the program. He possessed full authority over engineering, but he had to appeal to a vice-president if he could not resolve issues with his manufacturing counterpart. The program manager set the program milestones and assessed design and program status at periodic technical and management reviews. Development risk assessment was also under his purview, but it was not effectively carried out in the beginning of development.

Helping him keep track of the effort was the master schedules

group, which had the capability to assess schedule impacts to the overall program when problems appeared. The program manager's activities were also supported by a computerized cost accounting system that, although not very timely, provided an adequate level of visibility into cost performance. Such tools were critical to providing control in a less than ideal development environment.

**Development Environment**

The MD-11 was developed with the customer in mind, but direct interaction between Douglas designers and potential airline customers was minimal. Marketing surveys were the key means of obtaining information on top-level airline requirements and desires throughout the first phases of development. Although airlines that had placed firm orders were able to order custom features, most of the MD-11's design details were left to the Douglas engineers to determine without customer review or comment. The one exception was the MD-11 flight deck design which evolved directly from a collaboration between Douglas and pilots from potential customer airlines.

If airlines had been invited to review the MD-11 design at periodic design and program reviews, they would have seen the detailed technical requirements and design change considerably during development and production. Only a few of these alterations originated with the customers since the airlines had

not changed their minds as to what they fundamentally wanted from the MD-11. The changes were the result of the aircraft not being well specified up front by Douglas. Furthermore, due to the need to alleviate performance shortfalls, Douglas was continually introducing design fixes during development and production.

Program funding and workforce-level, while not terribly volatile, were not completely stable, either. During concept development, Douglas started hiring many people to prepare for FSED and production. However, once the program ramped up at full speed, the program was placed on hold as management tried to decide on the design configuration and whether the program should go ahead or not. Also, even though McDonnell Douglas had approved the three year budget of just over $500 million at the beginning of the program, the effort faced reduced funding during portions of FSED due to cash flow problems caused by the overrun. Both situations resulted in the temporary reduction of manpower.

Despite the funding reductions, the MD-11 received support from corporate management throughout development. The MD-11 program was initially sold to McDonnell Douglas corporate management as a low-risk derivative of the DC-10 that would only require small changes, resulting in a relatively short design and development cycle. Since McDonnell Douglas did not want to invest much of its capital in commercial aircraft, preferring the lower risk of government funded cost-plus development programs, approval was

predicated on the price being relatively low. The program cost estimate that Douglas gave to corporate management was low because it was based on assumptions of small changes that later turned out to be wrong. [Larson, 1995] While McDonnell Douglas was not pleased with the schedule slip and cost overrun, the program was still supported due to the projected profitability of the product line.

Along with corporate support, continuity of the key development team members was maintained to a moderately high degree. Despite the functional structure, specific engineers were assigned to the effort on a long term basis. Furthermore, many key designers and managers during concept development remained on the program when it entered FSED and production. The continuity of the development team and the stability of the organizational structure, though, were seriously impacted temporarily by the 1989 TQMS implementation.

During this transformation, the MD-11 program completely reorganized. Positions changed and everybody had to reapply for new positions. [Larson, 1995] Despite the chaos, most of the key designers and managers who had been on the program from the beginning eventually made it back under the new, integrated product teaming structure.

Douglas employees covered a broad range of expertise and background, and they did not always cooperate as well as they could have. This was true of the relationship between the Douglas engineering and manufacturing organizations. Douglas is a production oriented company in which the greatest amount of power is resident in the manufacturing organization. Like many other companies, Douglas had a cultural wall between the two disciplines. In the Douglas culture, manufacturing is never happy with what the engineering group gives them and viewed design engineering negatively as an overhead function that did not generate company revenues. [Larson, 1995] Even though the working-level relationships between engineering and manufacturing were positive, the company atmosphere did not promote closer working relationships. The implementation of the TQMS was partly meant to remove the barriers between them, but did not have immediate success.

Concerning the relationship between Douglas and the subcontractors, they can generally be described as businesslike, but not particularly close. As mentioned previously, poor specification development by Douglas and technical problems increased the amount and the scope of effort required from some of the subcontractors, resulting in conflicts involving legal actions. Although the TQMS was partly aimed at increasing cooperation between Douglas and its subcontractors, those relationships, at least initially, were not significantly

impacted positively or negatively by the change in organizational structure and operating philosophy, except it did create confusion as the Douglas points of contact continually changed.

Relations between Douglas and the airlines were good at the beginning, but again, not particularly close, since interaction with the customer was limited. When problems with the initial MD-11s surfaced, the relations with some MD-11 recipients turned negative. The large effort by Douglas to solve the problems was crucial to regaining the confidence of the customer airlines.

The means of interaction between all members of the MD-11 development team were primarily telephones, face-to-face meetings, and mail. While adequate, it was not an efficient arrangement for transferring large amounts of technical information. Also, meetings to coordinate activities and resolve problems with the subcontractors were expensive and required greater time to allow for travel since the MD-11 participants were widely distributed geographically. While most Douglas workers were located within several miles of each other in Long Beach, CA., everyone else was dispersed. Honeywell is in Phoenix, AZ., Pratt & Whitney and General Electric are on the East Coast, and the many other subcontractors and vendors were located throughout the United States and even the world. To facilitate communication, the key subcontractors had on-site representatives at Douglas facilities, and Douglas personnel spent a large amount

of time at the major subcontractor plants.

Douglas is a big company in a large corporation, and it had its share of bureaucratic procedures and approval chains to comply with during MD-11 development, as most other systems contractors. Furthermore, Douglas's configuration change control activities were not structured for quick and efficient changes. Despite these difficulties, Douglas did have the flexibility to tailor business relationships without significant government involvement as is the case in government sponsored projects. Workers followed the established procedures of Douglas Aircraft Company, and the top-level managers were given the responsibility and authority to carry out the development effort without micromanagement from the corporation. Not until the schedule slip and overrun started to materialize did corporate managers become more involved. This involvement was not all negative, since technical experts from outside of Douglas were provided to assist in solving the problems causing the delay. [Larson, 1995]

As for the numerous subcontractors and suppliers, they were managed in a traditional manner. That is, Douglas maintained oversight through on-site visits and correspondence, and the subcontractors were given the flexibility to do what they needed to do without burdensome procedures to follow.

As one of the biggest producers of large commercial jet aircraft

in the world, Douglas had a considerable amount of manufacturing expertise and experience inherent in its 4,000 to 6,000 workforce during the height of MD-11 development and production. At the beginning of the MD-11 effort, the company was solely a production house producing the MD-80 and DC-10, and it had not developed a new aircraft in years. Therefore, it did not possess a large pool of design engineering and development expertise. [Larson, 1995] As a consequence, a large number of engineers were hired to conduct the program. Although the engineering design team was technically capable, they of course lacked the experience of working together on a development program.

Given that the amount of profit obtained from the MD-11 is due significantly to the number of aircraft sold, given that the number of sales is tied to how well the MD-11 operates in service and satisfies the customers, and given that the future Douglas aircraft will be judged partly on the reputation of the MD-11, the company had a lot of incentive to ensure the MD-11 performed to customer expectations. The basic warranty offered to all MD-11 customers was supposed to ensure this. In addition to workmanship and parts quality provisions, Douglas guaranteed payload/range performance that would enable certain non-stop, international flights. While performance was not attained by the initial MD-11s delivered, Douglas developed modifications and retrofit the delivered aircraft.

**Summary/Conclusion**

The MD-11, intended as a low-risk redesign, turned out to be a complex systems integration effort. The development team failed to anticipate the integration challenges, and it was not structured to handle them efficiently. The nine month delivery delay of an original three year schedule and a 30 percent overrun are significant for a redesign that did not require breakthrough technology. Despite the problems with the development process, the eventual attainment of performance requirements, the potential for further improvements, and the number of orders ensuring program profitability to McDonnell Douglas suggest the MD-11 is a reasonably successful design.

Table 3.6-1 MD-11 Performance scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| TECHNICAL PERFORMANCE - INITIAL | 0-10 | 1 | 3 | 3 |
| TECHNICAL PERFORMANCE - MATURE | 0-10 | 1 | 10 | 10 |
| COST PERFORMANCE | 0-10 | 1 | 5 | 5 |
| SCHEDULE PERFORMANCE | 0-10 | 1 | 4 | 4 |
| PERFORMANCE TOTAL | | | | 22 |

Table 3.6-2 MD-11 Systems Engineering Fundamentals scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| REQUIREMENTS DEVELOPMENT | 0-10 | 2 | 2 | 4 |
| INCIPIENT SYSTEM DESIGN | 0-10 | 2 | 5 | 10 |
| EVALUATING ALTERNATIVE CONCEPTS AND DESIGNS | 0-10 | 1 | 6 | 6 |
| MAKE-OR-BUY DECISION | 0-10 | 1 | 8 | 8 |
| VALIDATION | 0-10 | 1 | 6 | 6 |
| VERIFICATION AND INTEGRATED TESTING | 0-10 | 1 | 7 | 7 |
| CONFIGURATION MANAGEMENT | 0-10 | 1 | 4 | 4 |
| MANUFACTURING CONSIDERATIONS | 0-10 | 1 | 6 | 6 |
| SYSTEMS INTEGRATION AND TECHNICAL MANAGEMENT | 0-10 | 1 | 5 | 5 |
| LIFE CYCLE CONSIDERATIONS | 0-10 | 1 | 7 | 7 |
| PROGRAM MANAGEMENT | 0-10 | 1 | 3 | 3 |
| SYSTEMS ENGINEERING FUNDAMENTALS TOTAL | | | | 66 |

Table 3.6-3 MD-11 Development Environment scores.

| Figures of Merit | Range | Weight | Rating | Score |
|---|---|---|---|---|
| EMPHASIS ON THE CUSTOMER | 0-10 | 1 | 6 | 6 |
| STABILITY OF REQUIREMENTS AND CONFIGURATION | 0-10 | 1 | 4 | 4 |
| FUNDING AND WORKFORCE-LEVEL STABILITY | 0-10 | 1 | 6 | 6 |
| STRONG SUPPORT FOR PROGRAM | 0-10 | 1 | 6 | 6 |
| CONTINUITY OF CORE DEVELOPMENT TEAM | 0-10 | 1 | 5 | 5 |
| STABILITY OF ORGANIZATIONAL STRUCTURE | 0-10 | 1 | 2 | 2 |
| COOPERATION AMONG ALL STAKEHOLDERS | 0-10 | 1 | 5 | 5 |
| EFFECTIVE COMMUNICATION WITHIN TEAM | 0-10 | 1 | 5 | 5 |
| FLEXIBILITY AND AUTONOMY | 0-10 | 1 | 6 | 6 |
| WORKFORCE EXPERTISE AND EXPERIENCE | 0-10 | 1 | 5 | 5 |
| ACCOUNTABILITY FOR SYSTEM PERFORMANCE | 0-10 | 1 | 8 | 8 |
| DEVELOPMENT ENVIRONMENT TOTAL | | | | 58 |

Table 3.6-4 MD-11 Design Difficulty scores.

| Elements | Range | Score |
|---|---|---|
| TYPE | 0-15 | 4 |
| KNOWLEDGE COMPLEXITY | 0-10 | 5 |
| STEPS | 0-10 | 9 |
| QUALITY IMPLEMENTATION EFFORT | 0-10 | 6 |
| MANUFACTURING OPERATIONS IMPLEMENTATION EFFORT | 0-5 | 4 |
| SELLING PRICE CONSTRAINT | 0-5 | 4 |
| DESIGN DIFFICULTY TOTAL | 0-55 | 32 |

Table 3.6-5 MD-11 Resources scores.

| Elements | Range | Score |
|---|---|---|
| COST | 0-15 | 10 |
| TIME | 0-10 | 6 |
| INFRASTRUCTURE | 0-10 | 7 |
| RESOURCES TOTAL | 0-35 | 23 |

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# CHAPTER 4

# RESULTS COMPARISON, ANALYSIS, AND DISCUSSION

The results of the case study ratings are summarized in Tables 4.1 through 4.5. The total scores were used to explore possible relationships between the characteristics of the system development process. Due to the limited number of data points, no strong conclusion can be made. However, as discussed later, there appears to be a generally positive relationship between the *performance* scores and the *systems engineering fundamentals* scores for the aircraft development case studies. Before exploring this issue, the cases are discussed in relation to one another.

The six case studies were presented in the order of higher to lower *systems engineering fundamentals* score, as indicated in Table 4.2. However, all six aircraft are considered successful systems in that they all operate to a high degree of ability, as indicated by the technical performance-mature figure of merit in Table 4.1. Combining technical performance with the cost and schedule performance figures of merit provides an effectiveness index of the overall system development process itself. The 777 development was by far the highest rated effort, and it was followed in order by the F-117, B-2, C-17, Model 60, and MD-11. Tables 4.2 and 4.3 clearly point out their main strengths and

Table 4.1 Summary of Performance scores.

| Figures of Merit | 777 | F-117 | B-2 | C-17 | Model 60 | MD-11 |
|---|---|---|---|---|---|---|
| TECHNICAL PERFORMANCE - INITIAL | 8 | 8 | 8 | 3 | 9 | 3 |
| TECHNICAL PERFORMANCE - MATURE | 10 | 10 | 9 | 9 | 10 | 10 |
| COST PERFORMANCE | 8 | 4 | 3 | 6 | 2 | 5 |
| SCHEDULE PERFORMANCE | 10 | 4 | 4 | 5 | 4 | 4 |
| ERFORMANCE TOTAL | 36 | 26 | 24 | 23 | 25 | 22 |

Table 4.2 Summary of Systems Engineering Fundamentals scores.

| Figures of Merit | 777 | F-117 | B-2 | C-17 | Model 60 | MD-11 |
|---|---|---|---|---|---|---|
| REQUIREMENTS DEVELOPMENT | 20 | 18 | 16 | 16 | 2 | 4 |
| INCIPIENT SYSTEM DESIGN | 18 | 18 | 16 | 14 | 14 | 10 |
| EVALUATING ALTERNATIVE CONCEPTS AND DESIGNS | 10 | 10 | 10 | 8 | 6 | 6 |
| MAKE-OR-BUY DECISION | 10 | 10 | 9 | 9 | 8 | 8 |
| VALIDATION | 9 | 9 | 9 | 8 | 5 | 6 |
| VERIFICATION AND INTEGRATED TESTING | 10 | 8 | 10 | 8 | 8 | 7 |
| CONFIGURATION MANAGEMENT | 10 | 9 | 7 | 3 | 7 | 4 |
| MANUFACTURING CONSIDERATIONS | 9 | 6 | 9 | 6 | 5 | 6 |
| SYSTEMS INTEGRATION AND TECHNICAL MANAGEMENT | 10 | 10 | 7 | 4 | 7 | 5 |
| LIFE CYCLE CONSIDERATIONS | 10 | 6 | 10 | 8 | 7 | 7 |
| PROGRAM MANAGEMENT | 10 | 9 | 7 | 3 | 6 | 3 |
| SYSTEMS ENGINEERING FUNDAMENTALS TOTAL | 126 | 113 | 110 | 87 | 75 | 66 |

Table 4.3 Summary of Development Environment scores.

| Figures of Merit | 777 | F-117 | B-2 | C-17 | Model 60 | MD-11 |
|---|---|---|---|---|---|---|
| EMPHASIS ON THE CUSTOMER | 10 | 9 | 9 | 7 | 6 | 6 |
| STABILITY OF REQUIREMENTS AND CONFIGURATION | 8 | 7 | 3 | 2 | 3 | 4 |
| FUNDING AND WORKFORCE-LEVEL STABILITY | 9 | 10 | 9 | 2 | 8 | 6 |
| STRONG SUPPORT FOR PROGRAM | 10 | 10 | 6 | 3 | 8 | 6 |
| CONTINUITY OF CORE DEVELOPMENT TEAM | 9 | 10 | 8 | 2 | 10 | 5 |
| STABILITY OF ORGANIZATIONAL STRUCTURE | 9 | 9 | 9 | 1 | 9 | 2 |
| COOPERATION AMONG ALL STAKEHOLDERS | 9 | 9 | 9 | 3 | 8 | 5 |
| EFFECTIVE COMMUNICATION WITHIN TEAM | 9 | 8 | 7 | 4 | 5 | 5 |
| FLEXIBILITY AND AUTONOMY | 7 | 8 | 7 | 5 | 8 | 6 |
| WORKFORCE EXPERTISE AND EXPERIENCE | 8 | 9 | 8 | 5 | 8 | 5 |
| ACCOUNTABILITY FOR SYSTEM PERFORMANCE | 8 | 8 | 7 | 8 | 6 | 8 |
| DEVELOPMENT ENVIRONMENT TOTAL | 96 | 97 | 82 | 42 | 79 | 58 |

Table 4.4 Summary of Design Difficulty scores.

| Elements | 777 | F-117 | B-2 | C-17 | Model 60 | MD-11 |
|---|---|---|---|---|---|---|
| TYPE | 9 | 13 | 13 | 9 | 3 | 4 |
| KNOWLEDGE COMPLEXITY | 6 | 8 | 8 | 6 | 4 | 5 |
| STEPS | 9 | 8 | 9 | 9 | 6 | 9 |
| QUALITY IMPLEMENTATION EFFORT | 9 | 7 | 8 | 6 | 5 | 6 |
| MANUFACTURING OPERATIONS IMPLEMENTATION EFFORT | 4 | 4 | 5 | 4 | 3 | 4 |
| SELLING PRICE CONSTRAINT | 4 | 1 | 1 | 2 | 4 | 4 |
| DESIGN DIFFICULTY TOTAL | 41 | 41 | 44 | 36 | 25 | 32 |

Table 4.5 Summary of Resources scores.

| Elements | 777 | F-117 | B-2 | C-17 | Model 60 | MD-11 |
|---|---|---|---|---|---|---|
| COST | 12 | 9 | 12 | 10 | 9 | 10 |
| TIME | 7 | 7 | 8 | 8 | 5 | 6 |
| INFRASTRUCTURE | 8 | 8 | 8 | 8 | 6 | 7 |
| RESOURCES TOTAL | 27 | 24 | 28 | 26 | 20 | 23 |

weaknesses in terms of the *systems engineering fundamentals* and *development environment*.

The Boeing 777 development has shown itself to be successful by its on-time production and delivery of an aircraft meeting customer requirements. The 777 received the highest ratings of all six cases in *performance* (36) and *systems engineering fundamentals* (126), and second highest in *development environment* (96). Boeing effectively utilized the full range of systems engineering principles, tasks, and techniques through implementation of concurrent engineering. Boeing also created an environment that strongly supported the work and communication of the interdisciplinary design/build teams. The success is due specifically to thorough requirements generation, the close participation of the airline customers throughout the entire development, the advanced computer aided design and manufacturing system, and the longer planned full-scale engineering development (FSED) schedule that ensured development problems were worked out before the first customer delivery. The result was a development with no apparent areas of significant weakness.

The next two aircraft, the F-117 and the B-2, are both revolutionary aircraft of high design difficulty and technical risk that followed strong systems engineering practices to help develop the highly integrated designs. Both aircraft possessed strong technical performance from their introductions, and they

have satisfied their Air Force customer. Schedule and cost performances, however, were not laudatory, especially for Northrop. The uncertainties surrounding the development of complex, breakthrough technologies certainly contributed to cost growth and delays, and the highly integrated nature of both designs generated many new issues to resolve. This is true despite the fact that both programs carried out extensive risk reduction activities prior to entering FSED. Furthermore, as classified military efforts, both were developed by highly skilled and motivated workers in highly stable environments that maintained strong funding and political support throughout most of their respective FSED phases. Further countering the favorable environment for the B-2 was a major requirements change from the Air Force early in FSED, resulting in a costly redesign and an extension in schedule. The momentum of the B-2 program was also affected by the Air Force's delay in starting FSED to accommodate the resurrected B-1 program. The F-117 did not experience a major change in customer requirements like the B-2, but its FSED schedule and budget were impacted by the crash of the first production aircraft due to an assembly error not detected during ground inspection and testing.

Despite both efforts strongly following systems engineering principles, the aircraft were developed differently. While the smaller F-117 was designed and fabricated by a relatively small project team in accordance with the philosophy of the Lockheed

Skunk Works, Northrop developed a new approach to develop the large B-2. Interestingly, most of Northrop's approach was later adopted by Boeing, a B-2 subcontractor, for its development of the 777.

Both the B-2 and 777 centered their efforts around a digital "paperless" database, set up extensive in-house integration testing laboratories, utilized an avionics test bed using other aircraft, and planned for extensive flight testing beyond what was required for certification. One major difference was the way the efforts were organized. Northrop had a functionally oriented team that used an informal zone management structure to deal with interdisciplinary and interface issues, whereas Boeing developed formal product teams. Furthermore, Boeing's computer aided design and manufacturing system was also more advanced. It was able to perform virtual prototyping, thereby identifying interface problems automatically on computer. Therefore, Boeing essentially refined and successfully implemented the development approach that Northrop had pioneered. The B-2 and 777 examples are significant in that they indicate the direction all aircraft development is moving to deal with increasing degrees of aircraft complexity and integration.

Of comparable design difficulty to the 777 was the C-17 military transport. However, its *performance* score of 23 is significantly lower in comparison. Despite a high mature technical performance

score, the initial technical performance was not acceptable, and cost and schedule performances have been marginal. While the early requirements development and design work with the Air Force were commendable, actions by Douglas throughout FSED as well as imposed conditions have resulted in great difficulties. Perhaps as its first mistake, Douglas contributed to its many eventual problems by accepting more stringent performance requirements than what the customer had originally requested.

Much of the *performance* characteristic shortfalls, however, have been due to poor management on the contractor's part. Douglas's configuration and production management systems were inadequate, and its program management function was ineffective. These problems enhanced as well as were enhanced by a very volatile environment, much of it defined by numerous design changes, high rates of repair and rework, the massive Total Quality Management System (TQMS) reorganization, opposition from Congress, acrimonious relations with the customer, and continuous turnover of the workforce. Further contributing to some of the instability was the long, drawn-out schedule with delayed FSED start. The C-17 development evidences many of the same problems as the MD-11, which was developed by the commercial sector of the same contractor during the same time.

The Learjet Model 60 was rated with a high technical performance score. However, like most of the other aircraft presented, the

overall *performance* score was tempered somewhat by low schedule and cost performance scores. For the relatively uncomplicated redesign effort by a small development team that carried out many of the fundamental systems engineering practices to a reasonable degree, this is unfortunate. Learjet's major shortcoming with the Model 60 effort was poor requirements development stemming from the lack of communication and coordination between the sales department and the engineering group. This situation resulted in a redirection after the initial design had been completed. With the exception of the changing requirements and internal communication problems, the small team development environment was quite conducive to systems engineering activities.

Like the Model 60, the MD-11 was a stretched version of an existing airframe with improved integrated avionics, engines, and aerodynamics. Also like the Model 60, one of the MD-11's biggest problems dealt with requirements development. The failure to develop a single, distinct specification for the MD-11 before FSED and the attendant underestimation of the incipient system design effort helped lead to the unanticipated systems and interface problems. Such problems were exacerbated by marginally effective mechanisms for configuration and production management as well as a development environment not highly supportive of strong systems engineering activities. The situation worsened during the poorly executed McDonnell Douglas TQMS reorganization, thereby greatly impacting progress on the MD-11 effort towards

the end of FSED. Consequently, the *performance* score reflects only a moderate overall success, having been downgraded by the schedule delays, cost growth, and problems with initially delivered aircraft.

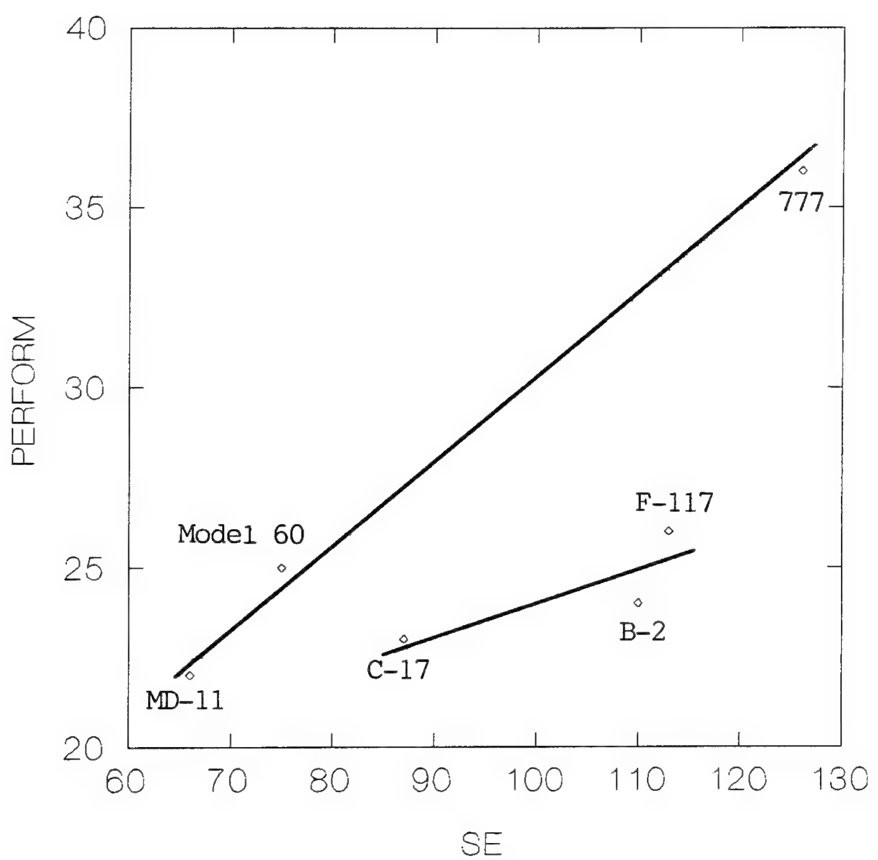
The picture that emerges most prominently from the aircraft case studies is that poor requirements development, inadequate configuration management, and weak program and technical management appear to be the primary determinants of lower *systems engineering fundamentals* scores. Significant *development environment* instability is reflected in the scores of several of the cases as well, primarily in the categories of stability of requirements and configuration, funding and workforce-level stability, strong support of program, continuity of core team members, stability of organizational structure, and cooperation of all stakeholders. Whether or not these areas are the primary detriments to *development environment* scores for other categories of systems is not known.

Comparing the *systems engineering fundamentals* scores for the cases, the military programs appear to tend towards higher scores. This is probably due to the fact that the government usually mandates a high degree of systems engineering on its large system development efforts. However, a commercial program received the highest *systems engineering fundamentals* score.

An important question to consider now is whether or not the case study ratings suggest anything about a possible relationship between *systems engineering fundamentals* and *performance.* To explore this issue, a simple graphical analysis was used.

Figure 4.1 is a plot of the *systems engineering fundamentals* (SE) scores versus the *performance* scores (Performance). The plot illustrates a generally positive relationship between the two characteristics. If the scoring methodology is valid, then this would indicate that the higher the degree of systems engineering performed, the higher the success of a system development effort.

Figure 4.1 Systems Engineering Fundamentals (SE) vs. Performance



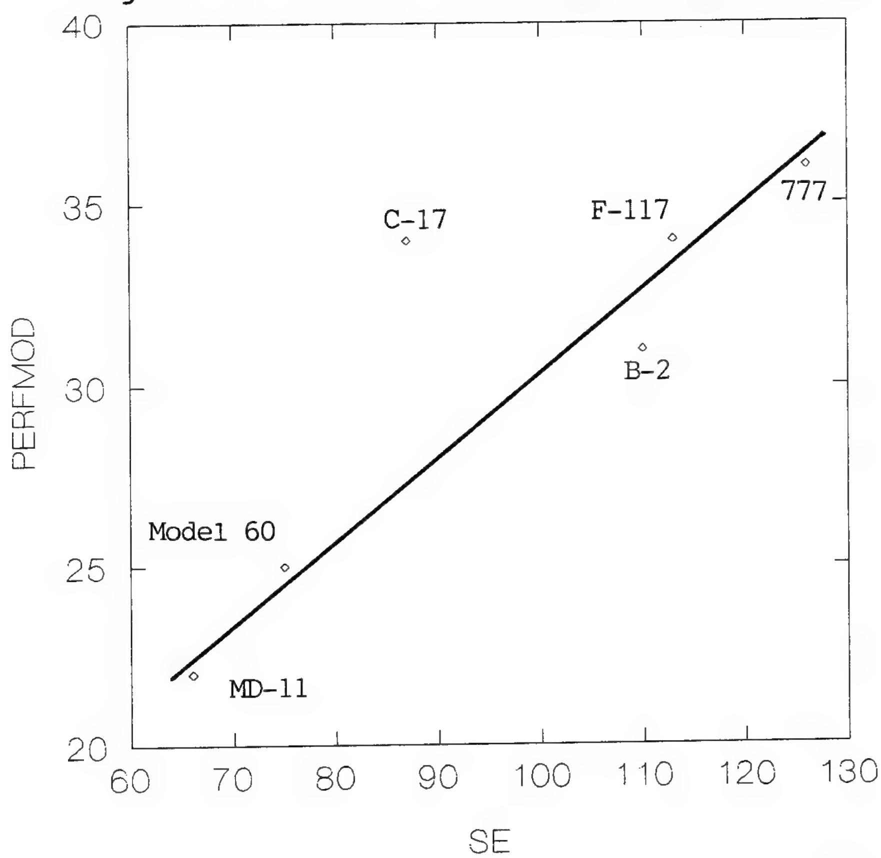
The commercial aircraft appear to follow the pattern better than the military aircraft. The 777, Model 60, and MD-11 fall nearly in a straight line, while the three military aircraft fall below it and appear to be aligned with a smaller slope. The points that are farthest from the trend line are the F-117 and the B-2. The *performance* scores for these two breakthrough designs may be adversely affected by the significant *design difficulty* and technical risk associated with each. If this is accurate, then *design difficulty* could possibly be used in a methodology to generate a multiplicative factor to adjust the *performance* scores closer to the commercial aircraft trend line.

The C-17 is also below the trend line, but its *design difficulty* is not as high as the stealth aircraft. However, the deviation may be attributed to the program's volatile environment as reflected by its low *development environment* score. This also suggests that perhaps a multiplicative factor methodology may be developed based on *development environment* scores to help bring the plots of all the efforts in line.

As just discussed, the plot locations of the government programs in Figure 4.1 can probably be explained by both the differences in *design difficulty* and *development environment*. However, another possible way of looking at the discrepancies may be simply in terms of government versus commercial. Perhaps a single multiplicative factor based only on whether or not the

development was a government effort can be developed. Since all three military efforts had generally marginal cost and schedule performance, this suggests that the development process for government aircraft is inherently more prone to cost and schedule difficulties. By multiplying those figures of merit scores by a factor of two, the performance numbers are enhanced. The modified numbers are presented in Figure 4.2.

Figure 4.2 SE vs. Performance (modified)




Whether such a factor, or other potential factors mentioned, is valid is mere speculation without further data to analyze. Therefore, the impact of *design difficulty*, *development environment*, and government procedures in the system development

process is an area requiring further study.

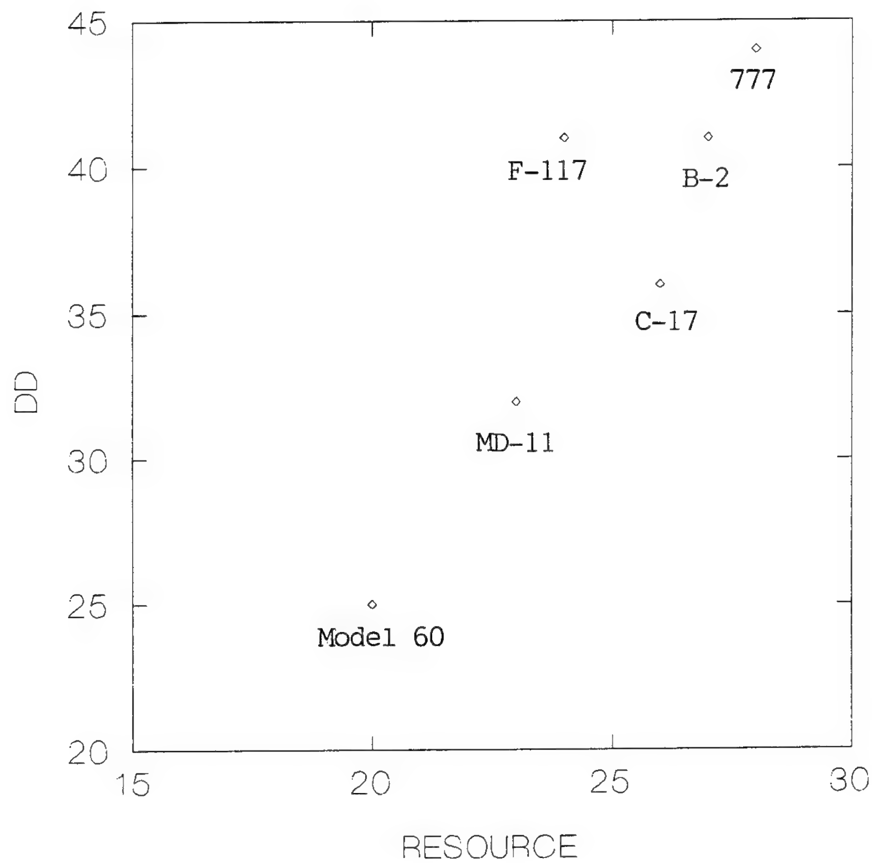
One characteristic of the system development process not discussed yet is *resources*. The *resources* scores were fairly comparable for all the aircraft, as shown in Table 4.5. This is reasonable, in that all large and highly complex aircraft need most of the same types of components and subsystems and utilize much of the same supplier infrastructure.

The results of plotting *design difficulty* versus *resources*, as in William L. Chapman's Ph.D. dissertation referenced in Chapter 1, are shown in Figure 4.3. This indicates that aircraft generally follow a linear relationship with regard to the two characteristics. Although Chapman concluded that, across all system designs, the two characteristics were not linearly related, he did recognize that the plotted points of systems within some categories are grouped together.

While far from being significant evidence, the graphs do provide at least a hint of support for the contentions expressed above, thereby suggesting that the methodology and approach proposed by this thesis may have some merit. However, further work is needed to support this assertion.

While much effort went into the development of the rating methodology, it is conceded that improvements can be made. Some

Figure 4.3 Design Difficulty vs. Resources




ideas that may enhance the process are provided as follows.

The figures of merit for *systems engineering fundamentals* can be considered reasonably complete based on the existing systems engineering literature. However, they may be broken out in different combinations than what was presented. As for the *development environment* figures of merit, they could be refined in some instances to be more precise and measurable. Perhaps the most important issue that needs further attention is the relative weighting between the figures of merit within the system

development characteristics. It may be appropriate to make modifications if justification can be found. Review of the characteristics, figures of merit, and rating criteria, and scoring system by others in the fields of systems engineering, engineering management, organizational effectiveness, and decision analysis would be helpful towards making improvements.

In addition to investigating possible refinements to the methodology, additional case studies are required to provide data to support or refute the methodology presented and the assertions made earlier. Additional aircraft data points are needed to provide a statistically significant database to allow a more rigorous analysis to be conducted to test whether or not the results presented above represent more than coincidence. Furthermore, cases are needed from other than aircraft systems to determine if the suggested positive relationship between *systems engineering fundamentals* and *performance* hold up for all categories of systems, from complex consumer electronics to large construction projects. Also, any further investigation should attempt to determine how design difficulty and the level of resources relate to the outcomes of the overall system development process. Additional work will help determine if the proposed methodology provides for valid "apples-to-apples" comparison between widely different categories of systems.

# CHAPTER 5

# VALIDATION OF METHODOLOGY

The case study evaluation and scoring methodology presented and demonstrated in this thesis was subjected to a validation trial. Nine engineers consisting of eight graduate students and a professor in Systems Engineering at the University of Arizona read versions of the case studies and rated them according to the methodology. The scores were compiled for each characteristic for each case, and the range, average, and standard deviation (S.D.) of each were used in comparing them to the ratings given by the author.

The mean and variability of the engineers' scores were calculated as a way of assessing how clearly the cases were written and the rating criteria were defined. If the scores for a particular figure of merit were widely varied for all of the case studies, then it would suggest that the rating criterion would need to be more specific. If the scores for a particular figure of merit for a particular case varied widely, it would suggest that a portion of that case would need to be rewritten to make it clearer. If the average of the scores were significantly different from the rating assigned by the author, it would suggest that the case, the criteria, or both would need to be modified. Finally, such differences could also indicate an inaccuracy or error with the

author's rating.

The results are presented in Table 5.1 through Table 5.24. They show the differences between and similarities with the nine engineers' ratings and the author's ratings.

In a few instances, figures of merit and elements and their corresponding criteria changed after the validation trial for reasons not directly related to the trial. Those figures of merit and elements are outlined in gray, and they are not useful data points in relation to assessing the final methodology. The new figures of merit and elements are listed with some of their boxes blackened since they were not used during the validation run. The rows that do not have any shading represent figures of merit and elements that remain with possible minor modifications from the original methodology.

The figures of merit and elements with average scores differing by two or more from the author's scores (accuracy criterion) and with standard deviations of two or greater (precision criterion) were closely scrutinized. Tables 5.31 through 5.35 are analyses of the results presented by system development characteristic, and they indicate whether or not the figures of merit and elements were subject to reevaluation due to violating the accuracy criterion, the precision criterion, or both.

Since the analyses did not identify any figures of merit or elements with problems across all the case studies, the author concentrated on modifying the individual cases. However, make-or-buy figure of merit was modified to make it clearer. Although the *design difficulty* element, type, appears to have a problem, the author chose to deal with the score variability through case study improvement.

A wide range of scores is evident for some of the case studies. This reflects differences in understanding and perception among the participants and is to be expected for people who have not been exposed to the methodology before.

As mentioned earlier, several figures of merit and elements were changed for reasons other than the validation results. Technical performance was split into two measures to enable easier evaluation, and two *design difficulty* elements, quality and quantity, were eliminated and replaced by quality implementation effort, manufacturing operations implementation effort, and selling price constraint. They were deemed to be more significant and appropriate measures.

While the validation results motivated the review of a number of figures of merit and elements and the cases themselves, it is interesting to note that the average of each characteristic total score (as well as the total of the average) from the validation

group compared favorably with the author's total scores. This is true especially for the ratings for *systems engineering fundamentals*. This suggests that on average, the group judgment will produce a numerical score reasonably close to that presented by the author. The author suggests that the improvements made to the case studies and people's greater experience with the methodology will improve the accuracy and precision of the scores. An additional validation run using engineers is recommended to test this assertion.

Table 5.1 Validation Data - 777 Performance scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| TECHNICAL PERFORMANCE | 9 | 8 | 8.75 | .46 | 8 | |
| TECHNICAL PERFORMANCE - INITIAL | | | | | | 8 |
| TECHNICAL PERFORMANCE - MATURE | | | | | | 10 |
| COST PERFORMANCE | 10 | 7 | 8.50 | 1.07 | 8 | 8 |
| SCHEDULE PERFORMANCE | 10 | 8 | 9.38 | .92 | 10 | 10 |
| PERFORMANCE TOTAL | 29 | 23 | 26.63<br>26.75 | 2.25 | 26 | 36 |

Table 5.2 Validation Data - F-117 Performance scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| TECHNICAL PERFORMANCE | 10 | 8 | 8.89 | .93 | 9 | |
| TECHNICAL PERFORMANCE - INITIAL | | | | | | 8 |
| TECHNICAL PERFORMANCE - MATURE | | | | | | 10 |
| COST PERFORMANCE | 10 | 4 | 8.67 | 2.00 | 4 | 4 |
| SCHEDULE PERFORMANCE | 9 | 3 | 6.44 | 2.40 | 4 | 4 |
| PERFORMANCE TOTAL | 28 | 18 | 24.00<br>24.00 | 3.39 | 17 | 26 |

Table 5.3 Validation Data - B-2 Performance scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| TECHNICAL PERFORMANCE | 10 | 8 | 8.44 | .73 | 8 | |
| TECHNICAL PERFORMANCE - INITIAL | | | | | | 8 |
| TECHNICAL PERFORMANCE - MATURE | | | | | | 9 |
| COST PERFORMANCE | 9 | 3 | 6.67 | 1.80 | 3 | 3 |
| SCHEDULE PERFORMANCE | 8 | 3 | 5.22 | 1.79 | 4 | 4 |
| PERFORMANCE TOTAL | 25 | 15 | 20.33<br>20.33 | 3.00 | 15 | 24 |

Table 5.4 Validation Data - C-17 Performance scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| TECHNICAL PERFORMANCE | 8 | 3 | 5.22 | 1.79 | 6 | |
| TECHNICAL PERFORMANCE - INITIAL | | | | | | 3 |
| TECHNICAL PERFORMANCE - MATURE | | | | | | 9 |
| COST PERFORMANCE | 6 | 2 | 4.78 | 1.64 | 6 | 6 |
| SCHEDULE PERFORMANCE | 6 | 2 | 3.67 | 1.32 | 5 | 5 |
| PERFORMANCE TOTAL | 18 | 7 | 13.67<br>13.67 | 3.81 | 17 | 23 |

Table 5.5 Validation Data - Model 60 Performance scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| TECHNICAL PERFORMANCE | 10 | 7 | 8.33 | 1.12 | 9 | |
| TECHNICAL PERFORMANCE - INITIAL | | | | | | 9 |
| TECHNICAL PERFORMANCE - MATURE | | | | | | 10 |
| COST PERFORMANCE | 6 | 1 | 5.44 | 1.67 | 6 | 2 |
| SCHEDULE PERFORMANCE | 8 | 4 | 4.44 | 1.33 | 4 | 4 |
| PERFORMANCE TOTAL | 22 | 14 | 18.21<br>18.22 | 2.28 | 19 | 25 |

Table 5.6 Validation Data - MD-11 Performance scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| TECHNICAL PERFORMANCE | 7 | 4 | 5.22 | .97 | 6 | |
| TECHNICAL PERFORMANCE - INITIAL | | | | | | 3 |
| TECHNICAL PERFORMANCE - MATURE | | | | | | 10 |
| COST PERFORMANCE | 6 | 3 | 5.25 | .46 | 5 | 5 |
| SCHEDULE PERFORMANCE | 4 | 2 | 3.56 | .73 | 4 | 4 |
| PERFORMANCE TOTAL | 16 | 10 | 14.03<br>13.78 | 2.11 | 15 | 22 |

Table 5.7 Validation Data - 777 Systems Engineering Fundamentals scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| REQUIREMENTS DEVELOPMENT | 10 | 8 | 9.63 | .74 | 10 | 10 x 2 |
| INCIPIENT SYSTEM DESIGN | 10 | 8 | 9.38 | .74 | 9 | 9 x 2 |
| EVALUATING ALTERNATIVE CONCEPTS AND DESIGNS | 10 | 7 | 9.13 | 1.13 | 9 | 10 |
| MAKE-OR-BUY DECISION | 10 | 7 | 9.38 | 1.19 | 9 | 10 |
| VALIDATION | 10 | 9 | 9.75 | .46 | 9 | 9 |
| VERIFICATION AND INTEGRATED TESTING | 10 | 7 | 9.25 | 1.04 | 9 | 10 |
| CONFIGURATION MANAGEMENT | 10 | 8 | 9.38 | .92 | 9 | 10 |
| MANUFACTURING CONSIDERATIONS | 10 | 8 | 9.38 | .92 | 9 | 10 |
| SYSTEMS INTEGRATION AND TECHNICAL MANAGEMENT | 10 | 7 | 9.50 | 1.07 | 9 | 10 |
| LIFE CYCLE CONSIDERATIONS | 10 | 8 | 9.63 | .74 | 9 | 9 |
| PROGRAM MANAGEMENT | 10 | 7 | 9.50 | 1.07 | 8 | 10 |
| SYSTEMS ENGINEERING FUNDAMENTALS TOTAL | 110 | 85 | 103.91<br>103.25 | 8.92 | 99 | 127 |

Table 5.8 Validation Data - F-117 Systems Engineering Fundamentals scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| REQUIREMENTS DEVELOPMENT | 10 | 8 | 9.11 | .78 | 9 | 9 x 2 |
| INCIPIENT SYSTEM DESIGN | 10 | 8 | 9.00 | .71 | 9 | 9 x 2 |
| EVALUATING ALTERNATIVE CONCEPTS AND DESIGNS | 10 | 7 | 8.56 | 1.01 | 9 | 10 |
| MAKE-OR-BUY DECISION | 10 | 0 | 8.00 | 3.08 | 9 | 10 |
| VALIDATION | 10 | 7 | 9.22 | 1.09 | 9 | 9 |
| VERIFICATION AND INTEGRATED TESTING | 10 | 8 | 9.33 | .87 | 9 | 8 |
| CONFIGURATION MANAGEMENT | 10 | 6 | 8.67 | 1.41 | 8 | 9 |
| MANUFACTURING CONSIDERATIONS | 10 | 1 | 6.33 | 3.16 | 5 | 6 |
| SYSTEMS INTEGRATION AND TECHNICAL MANAGEMENT | 10 | 7 | 9.00 | 1.00 | 10 | 10 |
| LIFE CYCLE CONSIDERATIONS | 8 | 3 | 6.33 | 1.66 | 5 | 6 |
| PROGRAM MANAGEMENT | 10 | 8 | 9.44 | .73 | 9 | 9 |
| SYSTEMS ENGINEERING FUNDAMENTALS TOTAL | 103 | 84 | 92.99<br>92.00 | 10.46 | 91 | 113 |

Table 5.9 Validation Data - B-2 Systems Engineering Fundamentals scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| REQUIREMENTS DEVELOPMENT | 10 | 7 | 9.00 | 1.00 | 8 | 8 x 2 |
| INCIPIENT SYSTEM DESIGN | 10 | 7 | 8.44 | .88 | 8 | 8 x 2 |
| EVALUATING ALTERNATIVE CONCEPTS AND DESIGNS | 10 | 6 | 9.11 | 1.36 | 9 | 10 |
| MAKE-OR-BUY DECISION | 10 | 6 | 9.11 | 1.27 | 9 | 9 |
| VALIDATION | 10 | 8 | 9.33 | .87 | 9 | 9 |
| VERIFICATION AND INTEGRATED TESTING | 10 | 7 | 9.11 | 1.05 | 9 | 10 |
| CONFIGURATION MANAGEMENT | 9 | 6 | 7.56 | 1.01 | 7 | 7 |
| MANUFACTURING CONSIDERATIONS | 10 | 7 | 8.78 | 1.30 | 9 | 9 |
| SYSTEMS INTEGRATION AND TECHNICAL MANAGEMENT | 10 | 6 | 8.00 | 1.32 | 8 | 7 |
| LIFE CYCLE CONSIDERATIONS | 10 | 7 | 9.33 | 1.12 | 9 | 10 |
| PROGRAM MANAGEMENT | 10 | 8 | 8.56 | .73 | 7 | 7 |
| SYSTEMS ENGINEERING FUNDAMENTALS TOTAL | 106 | 81 | 96.33<br>95.78 | 8.38 | 92 | 110 |

Table 5.10 Validation Data - C-17 Systems Engineering Fundamentals scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| REQUIREMENTS DEVELOPMENT | 8 | 3 | 6.67 | 1.73 | 8 | 8 X 2 |
| INCIPIENT SYSTEM DESIGN | 10 | 5 | 7.00 | 2.18 | 6 | 7 X 2 |
| EVALUATING ALTERNATIVE CONCEPTS AND DESIGNS | 10 | 3 | 7.22 | 2.28 | 8 | 8 |
| MAKE-OR-BUY DECISION | 10 | 4 | 7.67 | 2.00 | 9 | 9 |
| VALIDATION | 10 | 5 | 6.78 | 2.11 | 8 | 8 |
| VERIFICATION AND INTEGRATED TESTING | 9 | 3 | 7.22 | 1.99 | 8 | 8 |
| CONFIGURATION MANAGEMENT | 6 | 0 | 3.00 | 1.80 | 3 | 3 |
| MANUFACTURING CONSIDERATIONS | 7 | 0 | 3.22 | 2.22 | 5 | 6 |
| SYSTEMS INTEGRATION AND TECHNICAL MANAGEMENT | 7 | 3 | 4.78 | 1.39 | 4 | 4 |
| LIFE CYCLE CONSIDERATIONS | 10 | 7 | 7.78 | 1.48 | 7 | 8 |
| PROGRAM MANAGEMENT | 6 | 0 | 3.11 | 1.83 | 3 | 3 |
| SYSTEMS ENGINEERING FUNDAMENTALS TOTAL | 77 | 39 | 64.45<br>64.67 | 15.02 | 69 | 87 |

Table 5.11 Validation Data - Model 60 Systems Engineering Fundamentals scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| REQUIREMENTS DEVELOPMENT | 6 | 1 | 3.89 | 2.09 | 1 | 1 x 2 |
| INCIPIENT SYSTEM DESIGN | 9 | 5 | 7.11 | 1.36 | 7 | 7 x 2 |
| EVALUATING ALTERNATIVE CONCEPTS AND DESIGNS | 8 | 2 | 5.33 | 2.50 | 7 | 6 |
| MAKE-OR-BUY DECISION | 10 | 3 | 6.56 | 2.19 | 8 | 8 |
| VALIDATION | 7 | 5 | 5.67 | 1.32 | 7 | 5 |
| VERIFICATION AND INTEGRATED TESTING | 9 | 5 | 6.89 | 1.54 | 8 | 8 |
| CONFIGURATION MANAGEMENT | 10 | 5 | 6.67 | 1.50 | 7 | 7 |
| MANUFACTURING CONSIDERATIONS | 9 | 3 | 5.44 | 2.01 | 4 | 5 |
| SYSTEMS INTEGRATION AND TECHNICAL MANAGEMENT | 10 | 5 | 7.78 | 1.79 | 7 | 7 |
| LIFE CYCLE CONSIDERATIONS | 8 | 4 | 5.44 | 1.42 | 6 | 7 |
| PROGRAM MANAGEMENT | 9 | 5 | 7.11 | 1.27 | 6 | 6 |
| SYSTEMS ENGINEERING FUNDAMENTALS TOTAL | 83 | 59 | 67.89<br>68.11 | 9.60 | 68 | 75 |

Table 5.12 Validation Data - MD-11 Systems Engineering Fundamentals scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| REQUIREMENTS DEVELOPMENT | 5 | 2 | 3.78 | 1.30 | 3 | 2 x 2 |
| INCIPIENT SYSTEM DESIGN | 7 | 3 | 4.67 | 1.32 | 4 | 5 x 2 |
| EVALUATING ALTERNATIVE CONCEPTS AND DESIGNS | 8 | 4 | 6.22 | 1.56 | 7 | 6 |
| MAKE-OR-BUY DECISION | 10 | 4 | 7.78 | 1.72 | 7 | 8 |
| VALIDATION | 8 | 5 | 6.00 | 1.12 | 8 | 6 |
| VERIFICATION AND INTEGRATED TESTING | 10 | 5 | 7.44 | 1.67 | 7 | 7 |
| CONFIGURATION MANAGEMENT | 9 | 2 | 4.56 | 2.13 | 4 | 4 |
| MANUFACTURING CONSIDERATIONS | 8 | 3 | 4.67 | 1.66 | 5 | 6 |
| SYSTEMS INTEGRATION AND TECHNICAL MANAGEMENT | 7 | 3 | 4.78 | 1.20 | 5 | 5 |
| LIFE CYCLE CONSIDERATIONS | 10 | 5 | 7.67 | 2.18 | 7 | 7 |
| PROGRAM MANAGEMENT | 10 | 3 | 5.33 | 2.50 | 4 | 3 |
| SYSTEMS ENGINEERING FUNDAMENTALS TOTAL | 76 | 53 | 62.90<br>63.11 | 6.85 | 61 | 66 |

Table 5.13 Validation Data - 777 Development Environment scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| EMPHASIS ON THE CUSTOMER | 10 | 9 | 9.88 | .35 | 10 | 10 |
| STABILITY OF REQUIREMENTS AND CONFIGURATION | 10 | 7 | 8.87 | .99 | 7 | 8 |
| FUNDING AND WORKFORCE-LEVEL STABILITY | 10 | 8 | 9.50 | .76 | 9 | 9 |
| STRONG PROGRAM SUPPORT | 10 | 9 | 9.63 | .52 | 10 | 10 |
| CONTINUITY OF CORE DEVELOPMENT TEAM | 10 | 9 | 9.63 | .52 | 9 | 9 |
| STABILITY OF ORGANIZATIONAL STRUCTURE | 10 | 9 | 9.50 | .53 | 9 | 9 |
| COOPERATION AMONG ALL STAKEHOLDERS | 10 | 9 | 9.75 | .46 | 9 | 9 |
| EFFECTIVE COMMUNICATION WITHIN TEAM | 10 | 8 | 9.38 | .74 | 8 | 9 |
| FLEXIBILITY AND AUTONOMY | 10 | 8 | 9.25 | .89 | 7 | 7 |
| WORKFORCE EXPERTISE AND EXPERIENCE | 10 | 8 | 9.25 | .89 | 8 | 8 |
| ACCOUNTABILITY FOR SYSTEM PERFORMANCE | 10 | 8 | 9.25 | .89 | 8 | 8 |
| DEVELOPMENT ENVIRONMENT TOTAL | 110 | 92 | 103.89<br>103.75 | 6.07 | 94 | 96 |

Table 5.14 Validation Data - F-117 Development Environment scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| EMPHASIS ON THE CUSTOMER | 10 | 8 | 9.67 | .71 | 9 | 9 |
| STABILITY OF REQUIREMENTS AND CONFIGURATION | 10 | 7 | 8.78 | 1.20 | 8 | 7 |
| FUNDING AND WORKFORCE-LEVEL STABILITY | 10 | 8 | 9.67 | .71 | 10 | 10 |
| STRONG PROGRAM SUPPORT | 10 | 8 | 9.67 | .71 | 10 | 10 |
| CONTINUITY OF CORE DEVELOPMENT TEAM | 10 | 8 | 9.33 | .87 | 9 | 10 |
| STABILITY OF ORGANIZATIONAL STRUCTURE | 10 | 8 | 9.33 | .87 | 9 | 9 |
| COOPERATION AMONG ALL STAKEHOLDERS | 10 | 7 | 9.11 | 1.05 | 9 | 9 |
| EFFECTIVE COMMUNICATION WITHIN TEAM | 10 | 8 | 9.33 | .87 | 7 | 8 |
| FLEXIBILITY AND AUTONOMY | 10 | 8 | 9.33 | .87 | 8 | 8 |
| WORKFORCE EXPERTISE AND EXPERIENCE | 10 | 7 | 9.22 | 1.09 | 9 | 9 |
| ACCOUNTABILITY FOR SYSTEM PERFORMANCE | 10 | 8 | 9.11 | 1.05 | 8 | 8 |
| DEVELOPMENT ENVIRONMENT TOTAL | 110 | 85 | 102.55<br>101.78 | 8.41 | 96 | 97 |

Table 5.15 Validation Data - B-2 Development Environment scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| EMPHASIS ON THE CUSTOMER | 10 | 8 | 9.44 | .88 | 9 | 9 |
| STABILITY OF REQUIREMENTS AND CONFIGURATION | 10 | 1 | 5.44 | 2.46 | 3 | 3 |
| FUNDING AND WORKFORCE-LEVEL STABILITY | 9 | 3 | 5.89 | 1.90 | 9 | 9 |
| STRONG PROGRAM SUPPORT | 9 | 0 | 5.56 | 2.70 | 8 | 6 |
| CONTINUITY OF CORE DEVELOPMENT TEAM | 10 | 8 | 9.22 | .83 | 8 | 8 |
| STABILITY OF ORGANIZATIONAL STRUCTURE | 10 | 8 | 8.89 | .60 | 9 | 9 |
| COOPERATION AMONG ALL STAKEHOLDERS | 10 | 5 | 8.89 | 1.62 | 9 | 9 |
| EFFECTIVE COMMUNICATION WITHIN TEAM | 9 | 6 | 7.89 | .93 | 6 | 7 |
| FLEXIBILITY AND AUTONOMY | 10 | 7 | 8.67 | 1.41 | 7 | 7 |
| WORKFORCE EXPERTISE AND EXPERIENCE | 10 | 8 | 9.33 | 1.00 | 8 | 8 |
| ACCOUNTABILITY FOR SYSTEM PERFORMANCE | 10 | 7 | 8.78 | .97 | 7 | 7 |
| DEVELOPMENT ENVIRONMENT TOTAL | 97 | 74 | 88.00<br>88.67 | 8.32 | 83 | 82 |

Table 5.16 Validation Data - C-17 Development Environment scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| EMPHASIS ON THE CUSTOMER | 10 | 5 | 7.78 | 1.64 | 7 | 7 |
| STABILITY OF REQUIREMENTS AND CONFIGURATION | 6 | 0 | 3.11 | 2.26 | 2 | 2 |
| FUNDING AND WORKFORCE-LEVEL STABILITY | 6 | 0 | 2.78 | 1.79 | 2 | 2 |
| STRONG PROGRAM SUPPORT | 4 | 0 | 2.44 | 1.42 | 2 | 3 |
| CONTINUITY OF CORE DEVELOPMENT TEAM | 6 | 0 | 2.89 | 1.90 | 2 | 2 |
| STABILITY OF ORGANIZATIONAL STRUCTURE | 6 | 1 | 2.89 | 1.54 | 1 | 1 |
| COOPERATION AMONG ALL STAKEHOLDERS | 5 | 2 | 4.22 | 1.09 | 3 | 3 |
| EFFECTIVE COMMUNICATION WITHIN TEAM | 6 | 2 | 4.00 | 1.94 | 5 | 4 |
| FLEXIBILITY AND AUTONOMY | 7 | 3 | 4.44 | 1.42 | 5 | 5 |
| WORKFORCE EXPERTISE AND EXPERIENCE | 6 | 2 | 4.33 | 1.41 | 5 | 5 |
| ACCOUNTABILITY FOR SYSTEM PERFORMANCE | 8 | 6 | 7.22 | 1.72 | 8 | 8 |
| DEVELOPMENT ENVIRONMENT TOTAL | 48 | 37 | 46.10<br>45.78 | 7.90 | 42 | 42 |

Table 5.17 Validation Data - Model 60 Development Environment scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| EMPHASIS ON THE CUSTOMER | 8 | 2 | 5.78 | 2.05 | 6 | 6 |
| STABILITY OF REQUIREMENTS AND CONFIGURATION | 8 | 0 | 4.44 | 2.51 | 3 | 3 |
| FUNDING AND WORKFORCE-LEVEL STABILITY | 10 | 7 | 8.89 | 1.17 | 8 | 8 |
| STRONG PROGRAM SUPPORT | 10 | 8 | 9.11 | .93 | 7 | 8 |
| CONTINUITY OF CORE DEVELOPMENT TEAM | 10 | 7 | 9.22 | 1.20 | 10 | 10 |
| STABILITY OF ORGANIZATIONAL STRUCTURE | 10 | 8 | 9.33 | .87 | 9 | 9 |
| COOPERATION AMONG ALL STAKEHOLDERS | 10 | 5 | 7.78 | 1.48 | 7 | 8 |
| EFFECTIVE COMMUNICATION WITHIN TEAM | 10 | 3 | 6.67 | 2.65 | 8 | 5 |
| FLEXIBILITY AND AUTONOMY | 10 | 7 | 8.67 | 1.41 | 8 | 8 |
| WORKFORCE EXPERTISE AND EXPERIENCE | 10 | 7 | 9.00 | 1.22 | 8 | 8 |
| ACCOUNTABILITY FOR SYSTEM PERFORMANCE | 9 | 5 | 6.22 | 1.48 | 6 | 6 |
| DEVELOPMENT ENVIRONMENT TOTAL | 103 | 74 | 85.00<br>84.22 | 8.98 | 80 | 79 |

Table 5.18 Validation Data - MD-11 Development Environment scores.

| Figures of Merit | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| EMPHASIS ON THE CUSTOMER | 7 | 2 | 3.89 | 1.62 | 5 | 6 |
| STABILITY OF REQUIREMENTS AND CONFIGURATION | 4 | 3 | 3.56 | .53 | 4 | 4 |
| FUNDING AND WORKFORCE-LEVEL STABILITY | 9 | 2 | 5.78 | 2.28 | 6 | 6 |
| STRONG PROGRAM SUPPORT | 10 | 4 | 7.00 | 2.06 | 6 | 6 |
| CONTINUITY OF CORE DEVELOPMENT TEAM | 9 | 4 | 7.11 | 1.62 | 8 | 5 |
| STABILITY OF ORGANIZATIONAL STRUCTURE | 5 | 0 | 2.67 | 1.66 | 1 | 2 |
| COOPERATION AMONG ALL STAKEHOLDERS | 7 | 3 | 5.00 | 1.22 | 5 | 5 |
| EFFECTIVE COMMUNICATION WITHIN TEAM | 6 | 3 | 4.00 | 1.12 | 5 | 5 |
| FLEXIBILITY AND AUTONOMY | 10 | 2 | 6.44 | 2.19 | 6 | 6 |
| WORKFORCE EXPERTISE AND EXPERIENCE | 9 | 5 | 6.56 | 1.59 | 5 | 5 |
| ACCOUNTABILITY FOR SYSTEM PERFORMANCE | 10 | 5 | 7.56 | 1.67 | 8 | 8 |
| DEVELOPMENT ENVIRONMENT TOTAL | 76 | 42 | 59.57<br>60.44 | 10.01 | 59 | 58 |

Table 5.19 Validation Data - 777 Design Difficulty scores.

| Element | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| TYPE | 13 | 6 | 9.88 | 2.36 | 7 | 9 |
| KNOWLEDGE COMPLEXITY | 8 | 4 | 5.75 | 1.39 | 5 | 6 |
| STEPS | 10 | 8 | 9.25 | .71 | 10 | 9 |
| QUALITY | 10 | 5 | 8.13 | 1.55 | 10 | |
| QUALITY IMPLEMENTATION EFFORT | | | | | | 9 |
| QUANTITY | 3 | 3 | 3.00 | 0 | 3 | |
| MANUFACTURING OPERATIONS IMPLEMENTATION EFFORT | | | | | | 4 |
| SELLING PRICE CONSTRAINT | | | | | | 4 |
| DESIGN DIFFICULTY TOTAL | 42 | 28 | 36.01<br>35.75 | 4.71 | 35 | 41 |

Table 5.20 Validation Data - 777 Resources scores.

| Element | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| COST | 13 | 9 | 11.75 | 1.83 | 6 | 12 |
| TIME | 7 | 5 | 6.37 | .74 | 7 | 7 |
| INFRASTRUCTURE | 10 | 6 | 8.00 | 1.22 | 7 | 8 |
| RESOURCES TOTAL | 30 | 21 | 25.74<br>25.25 | 3.11 | 20 | 27 |

Table 5.21 Validation Data - F-117 Design Difficulty scores.

| Element | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| TYPE | 14 | 7 | 12.44 | 2.30 | 14 | 13 |
| KNOWLEDGE COMPLEXITY | 10 | 5 | 8.22 | 1.39 | 8 | 8 |
| STEPS | 9 | 6 | 8.11 | 1.36 | 10 | 8 |
| QUALITY | 10 | 7 | 8.67 | 1.12 | 10 | |
| QUALITY IMPLEMENTATION EFFORT | | | | | | 7 |
| QUANTITY | 3 | 2 | 2.22 | .44 | 2 | |
| MANUFACTURING OPERATIONS IMPLEMENTATION EFFORT | | | | | | 4 |
| SELLING PRICE CONSTRAINT | | | | | | 1 |
| DESIGN DIFFICULTY TOTAL | 44 | 31 | 39.66<br>39.67 | 4.09 | 44 | 41 |

Table 5.22 Validation Data - F-117 Resources scores.

| Element | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| COST | 13 | 9 | 10.78 | 2.86 | 6 | 9 |
| TIME | 10 | 3 | 5.89 | 2.85 | 7 | 7 |
| INFRASTRUCTURE | 10 | 2 | 6.67 | 2.50 | 8 | 8 |
| RESOURCES TOTAL | 30 | 17 | 23.34<br>24.44 | 4.00 | 21 | 24 |

Table 5.23 Validation Data - B-2 Design Difficulty scores.

| Element | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| TYPE | 15 | 12 | 13.44 | .88 | 14 | 13 |
| KNOWLEDGE COMPLEXITY | 10 | 7 | 8.33 | 1.12 | 8 | 8 |
| STEPS | 10 | 8 | 8.56 | 1.24 | 10 | 9 |
| QUALITY | 9 | 3 | 6.89 | 1.83 | 10 | |
| QUALITY IMPLEMENTATION EFFORT | | | | | | 8 |
| QUANTITY | 3 | 2 | 2.22 | .44 | 2 | |
| MANUFACTURING OPERATIONS IMPLEMENTATION EFFORT | | | | | | 5 |
| SELLING PRICE CONSTRAINT | | | | | | 1 |
| DESIGN DIFFICULTY TOTAL | 43 | 26 | 39.44<br>38.44 | 5.08 | 44 | 44 |

Table 5.24 Validation Data - B-2 Resources scores.

| Element | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| COST | 15 | 10 | 12.56 | 1.59 | 8 | 12 |
| TIME | 10 | 6 | 7.56 | 1.13 | 8 | 8 |
| INFRASTRUCTURE | 10 | 6 | 8.00 | 1.22 | 8 | 8 |
| RESOURCES TOTAL | 32 | 25 | 28.12<br>28.11 | 1.96 | 24 | 28 |

Table 5.25 Validation Data - C-17 Design Difficulty scores.

| Element | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| TYPE | 9 | 5 | 6.11 | 1.27 | 9 | 9 |
| KNOWLEDGE COMPLEXITY | 8 | 4 | 5.22 | 1.30 | 5 | 6 |
| STEPS | 10 | 7 | 8.44 | 1.24 | 10 | 9 |
| QUALITY | 7 | 4 | 5.33 | 1.22 | 8 | |
| QUALITY IMPLEMENTATION EFFORT | | | | | | 6 |
| QUANTITY | 4 | 2 | 2.67 | .71 | 3 | |
| MANUFACTURING OPERATIONS IMPLEMENTATION EFFORT | | | | | | 4 |
| SELLING PRICE CONSTRAINT | | | | | | 2 |
| DESIGN DIFFICULTY TOTAL | 31 | 25 | 27.77<br>27.78 | 2.22 | 35 | 36 |

Table 5.26 Validation Data - C-17 Resources scores.

| Element | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| COST | 14 | 10 | 11.11 | 1.54 | 7 | 10 |
| TIME | 10 | 3 | 8.33 | 2.45 | 8 | 8 |
| INFRASTRUCTURE | 10 | 3 | 7.44 | 2.01 | 7 | 8 |
| RESOURCES TOTAL | 33 | 18 | 26.88<br>26.89 | 4.37 | 22 | 26 |

Table 5.27 Validation Data - Model 60 Design Difficulty scores.

| Element | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| TYPE | 7 | 3 | 4.11 | 1.36 | 3 | 3 |
| KNOWLEDGE COMPLEXITY | 5 | 3 | 4.22 | .67 | 4 | 4 |
| STEPS | 10 | 5 | 7.11 | 2.57 | 8 | 6 |
| QUALITY | 8 | 5 | 6.22 | .83 | 8 | |
| QUALITY IMPLEMENTATION EFFORT | | | | | | 5 |
| QUANTITY | 4 | 2 | 2.78 | .67 | 3 | |
| MANUFACTURING OPERATIONS IMPLEMENTATION EFFORT | | | | | | 3 |
| SELLING PRICE CONSTRAINT | | | | | | 4 |
| DESIGN DIFFICULTY TOTAL | 29 | 17 | 24.44<br>24.44 | 3.71 | 26 | 25 |

Table 5.28 Validation Data - Model 60 Resources scores.

| Element | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| COST | 10 | 6 | 8.33 | 1.73 | 6 | 9 |
| TIME | 5 | 4 | 4.67 | .50 | 5 | 5 |
| INFRASTRUCTURE | 7 | 4 | 5.67 | 1.00 | 6 | 6 |
| RESOURCES TOTAL | 21 | 15 | 18.67<br>17.78 | 2.54 | 17 | 20 |

Table 5.29 Validation Data - MD-11 Design Difficulty scores.

| Element | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| TYPE | 6 | 3 | 5.00 | 1.12 | 3 | 4 |
| KNOWLEDGE COMPLEXITY | 6 | 3 | 4.67 | 1.12 | 4 | 5 |
| STEPS | 10 | 5 | 8.00 | 1.87 | 8 | 9 |
| QUALITY | 9 | 4 | 6.11 | 1.62 | 8 | |
| QUALITY IMPLEMENTATION EFFORT | | | | | | 6 |
| QUANTITY | 3 | 3 | 3.00 | 0 | 3 | |
| MANUFACTURING OPERATIONS IMPLEMENTATION EFFORT | | | | | | 4 |
| SELLING PRICE CONSTRAINT | | | | | | 4 |
| DESIGN DIFFICULTY TOTAL | 31 | 23 | 26.78<br>27.22 | 2.86 | 26 | 32 |

Table 5.30 Validation Data - MD-11 Resources scores.

| Element | High | Low | Avg. | S.D. | Thesis (Initial) | Thesis (Final) |
|---|---|---|---|---|---|---|
| COST | 13 | 8 | 10.22 | 2.05 | 6 | 10 |
| TIME | 6 | 5 | 5.44 | .53 | 5 | 6 |
| INFRASTRUCTURE | 8 | 5 | 6.67 | 1.00 | 6 | 7 |
| RESOURCES TOTAL | 27 | 18 | 22.33<br>22.33 | 2.83 | 17 | 23 |

Table 5.31 Performance Validation Analysis

| Case Study | Figure of Merit | Violates Accuracy | Violates Precision |
|---|---|---|---|
| F-117 | Schedule perform. | X | X |
| B-2 | Cost performance | X | |
| Model 60 | Cost performance | X | |

Table 5.32 Systems Engineering Fundamentals Validation Analysis

| Case Study | Figure of Merit | Violates Accuracy | Violates Precision |
|---|---|---|---|
| F-117 | Make-or-buy | | X |
| | Manufacturing considerations | | X |
| C-17 | Incipient system design | | X |
| | Evaluating alt. concepts | | X |
| | Make-or-buy | | X |
| | Validation | | X |
| | Manufacturing considerations | | X |
| Model 60 | Requirements development | X | |
| | Evaluating alt. concepts | | X |
| | Make-or-buy | | X |
| | Manufacturing considerations | | X |
| MD-11 | Validation | X | |
| | Configuration management | | X |
| | Life cycle considerations | | X |
| | Program managment | | X |

Table 5.33 Development Environment Validation Analysis

| Case Study | Figure of Merit | Violates Accuracy | Violates Precision |
|---|---|---|---|
| 777 | Flexibility and autonomy | X | |
| F-117 | Effective communication | X | X |
| B-2 | Stability of requirements | X | X |
| | Funding and workforce-level stability | X | |
| | Strong program support | X | X |
| C-17 | Stability of requirements | | X |
| Model 60 | Emphasis on the customer | | X |
| | Stability of requirements | | X |
| | Strong program support | X | |
| | Effective communication | | X |
| MD-11 | Funding and workforce-level stability | | X |
| | Strong program support | | X |
| | Flexibility and autonomy | | X |

Table 5.34 Design Difficulty Validation Analysis

| Case Study | Element | Violates Accuracy | Violates Precision |
|---|---|---|---|
| 777 | Type | X | X |
| F-117 | Type | | X |
| C-17 | Type | X | |
| Model 60 | Steps | | X |
| MD-11 | Type | X | |

Table 5.35 Resources Validation Analysis

| Case Study | Element | Violates Accuracy | Violates Precision |
|---|---|---|---|
| F-117 | Cost | | X |
| | Time | | X |
| | Infrastructure | | X |
| B-2 | Cost | X | |
| C-17 | Cost | X | |
| | Time | | X |
| | Infrastructure | | X |
| MD-11 | Cost | X | X |

# CHAPTER 6

# SUMMARY

This thesis has proposed a universal methodology to score case studies of system development efforts according to figures of merit and element rating criteria. Also proposed in an approach to explore the relationships between the characteristics of the system development process, particularly the magnitude of the application of systems engineering, and the degree to which that process is successful. Chapter 1 laid the foundation by pointing out that the lack of a common definition of systems engineering makes development of a rating system difficult, and it provided a model which provides the framework for the methodology. It also outlines the entire approach to investigating possible high level relationships.

Chapter 2 presents the rating criteria and scoring method for each of the figures of merit and elements for the five characteristics of the system development process.

Chapter 3 is composed of the six case studies of recent commerical and military aircraft which are rated using the proposed methodology. The cases are presented in the order of higher to lower *systems engineering fundamentals* scores, and they include the Boeing 777 commercial transport, Lockheed F-117

Stealth Fighter, Northrop B-2 Stealth Bomber, McDonnell Douglas C-17 military transport, Learjet Model 60 business jet, and McDonnell Douglas MD-11 commercial transport.

In Chapter 4, the cases are briefly compared and the results of the ratings are summarized, graphed, and analyzed. The graphs suggest a possible positive relationship between the *systems engineering fundamentals* score and the *performance* score for each case. The chapter also proposes possible refinements to the methodology and suggestions for additional data generation and analysis.

Chapter 5 presents the results of the validation run conducted by nine engineers help identify weaknesses in the case studies and evaluation methodology so that they could be improved. The results indicate close agreement between the group's average scores and the author's scores, indicating reasonable clarity of the cases and methodology.

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None of the pictures have evidence of copyright status.

# Appendix

# LEARJET MODEL 60 DEVELOPMENT QUESTIONNAIRE FOR CAPT JAY MOODY'S SYSTEMS ENGINEERING RESEARCH PROJECT

## DEVELOPMENT PROGRAM FEATURES

- Development Approach
  - -- traditional, skunkworks, integrated product development (concurrent engr)? SKUNK WORKS
- Organizational Structure (functional-matrix project team, project team, design/build teams, interface teams, other)? MATRIX PROJECT TEAM
- Average Size of Contractor Team during Development (including major subcontractors): AVERAGE 200
- Electronic communication links established between prime, subs, vendors, customers, users? NO
- Research cost: } APPROX 90 MILLION INCLUDING 3 SALEABLE ACFT
- Development cost: }
- Funding profile per fiscal year: PROBABLY ABOUT 30 MILLION / YR WITH THE 1ST FISCAL YR OF PROGRAM ONLY 6 MONTHS.
- % Overrun of development costs: ABOUT 20% IF YOU CONSIDER PROGRESSIVE PROGRAM CHANGES - ABOUT 200% ON INITIAL PROGRAM ESTIMATE
- Date of Program Start: JULY 90
- Advanced Development start/end dates: JULY 90 ~~- JAN 93~~
- Full-scale Engineering Development (FSED) (or EMD) start/ end dates: JULY 90 - JAN 93
- Development Length (years): 2 1/2 YRS
- Behind Schedule from original plan (months): ABOUT 6 MONTHS.
- Date of 1st Production Unit Delivery to customer: JAN 93.
- Number of production units ordered/on option: ON GOING - 33 ON ORDER BY 1ST DELIVERY
- Production delivery profile by year: FY94: 28, FY95: 33, FY96: 20, FY97: 18, FY98: 18, FY99: 18, FY2000: 18
- Production cost (first unit): ~ $9.5 MILLION
- Flyaway Cost/ Unit Production Sale Price: $8.6M without options and escallation

## MODELING AND ANALYSIS TOOLS

- Simulation modeling - what for?
  - -- Aerodynamics? (yes/no)
    - --- What programs? How used? Used TRANAIR CFD software program (full potential analysis code) on NASA-Ames Cray to model details and calculate shock waves for transonic performance.
  - -- Mechanical (structural, vibrational, thermal)? (yes/no)
    - --- What programs? How used? NASTRAN & FINITE ELEMENT MODELING

-- Electrical? (yes/no)
--- What programs? How used? AUTOCAD - MINOR WIRING DIAGRAM CHANGE

-- Hydraulics? (yes/no)
--- What programs? How used?

-- Other? How used?

- Wind Tunnel tests performed? What purposes?
HIGH SPEED TESTS TO CONFIRM WING & PYLON AERODYNAMIC CHANGES FOR REDUCED DRAG

- Mockups used? What kind/what for?
FUSELAGE MOCK-UP TO SHOW CABIN MODIFICATIONS

- Breadboards/brassboards used? (yes/no) How extensive?

- Prototypes used? (yes/no)
-- Advanced Technology, FSED, or Production prototypes? One engineering prototype and 4 preproduction prototypes were used for flight testing. The 4 preproduction prototypes were delivered to customers after completion of flight testing and FAA certification.
- How close were prototype configurations to production units configuration? (High, Medium, Low)
- Prototype delivery dates (1st, 2nd, 3rd, 4th, 5th, 6th, 7th)

**HARDWARE/SOFTWARE TESTING**

- Hardware-in-the-loop (HITL) simulation used? (yes/no)
- What major components tested in HITL?

- Component/subsystem testing - done early in dev? (yes/no)

- Use of airborne testbed for avionics? (yes/no)
  -- What aircraft and how used?
  60-002 Primarily autopilot development

- Use of ground test articles? (yes/no)
- Ground Testing (type, start, end)
  Fuselage pressurization tests.
  Flap, ldg gear & spoiler fatigue

- Number of Flight Test Aircraft: 4
- First Flight (date): July 1991
- Flight Testing - development and certification/operational- (type, start, end)
  1st unit:
  2nd unit:
  3rd unit:
  4th unit: function and reliability flight testing

- Flight Testing - total length (months): 18
- Reliability Testing? Component level? System level? Reliability flight testing (prototype #4)

- Logistics Testing? What kind? No.

  -- Performed early or late in developoment? NA.
- Major design changes due to FSED (EMD) testing? NA.

**SYSTEMS ENGINEERING TOOLS, TECHNIQUES, AND REQUIREMENTS**

- Company had/has a separate systems engineering organization working on the development program? (yes/no)
- Design approach: Requirements flowdown (top down) or bottoms up? BOTH
- Use of object oriented programming? (yes/no)
- Use of Integration Design/Manufacturing Technologies (design languages)? (yes/no) Prime contractor? or subcontractor level? For what?
  - -- CADD, CAD, CAE? ______
  - -- Computer aided software engineering (CASE)? UGII
  - -- 3-D Modeling? (yes/no) What % of design covered? NEW DETAIL ONLY
  - -- 3-D Solid modeling? (yes/no) What % of design covered? ______
  - -- CAM, CIM? (yes/no) YES
  - -- CAD/CAM integrated? (yes/no) PARTIAL
  - -- Paperless Design? (yes/no) How extensive? ______
  - -- Paperless Manufacturing Floor? (yes/no) How extensive? ______
  - -- Other? ______
- Work Breakdown Structure generated at beginning of program? (yes/no)
- Formal Design Reviews planned/conducted? (yes/no) With customers? Internal? What kind?
  - -- Systems requirements review? (yes/no) ______
  - -- Preliminary design review? (yes/no) ______
  - -- Critical design review (system)? (yes/no) ______
  - -- Critical design reviews (subsystems)? (yes/no) ______
  - -- Software walk-throughs? (yes/no) ENGINE FADEC'S ONLY
  - -- ______
  - -- ______
  - -- ______
  - -- ______
- Formalized configuration management system (yes/no)
  - -- Prime contractor has separate CM organization? (yes/no)
  - -- Established baselines/config items identified? (yes/no)
  - -- Change control system with a change control board? (yes/no)
  - -- Formal requirements auditing performed? (yes/no)
  - -- Maintains status accounting of Engineering change requests (ECRs), Failure Reports (FRs), and Action Items? (yes/no)
    - --- Computer based? (yes/no)
    - --- Failure Report and Corrective Action System (FRACAS)

established? (yes/no)
-- Level of Engineering Drawings Req'd/Generated (3, 4, 5, 6?)
- Miscellaneous
  -- Performed formalized tradeoff of major design options? (yes/no)
  -- Scheduling methods/programs used:
    --- Earned value system? (yes/no)
    --- PERT, Line of Balance, Gantt, Other? ________
  -- Computerized cost accounting system? (yes/no)
  -- Use of statistical process control? (yes/no)

**DOCUMENTATION REQUIRED/GENERATED**

Did/does the program have:
- Systems Engineering Management Plan or equivalent? (yes/no)
- Test and Evaluation Master Plan or equivalent? (yes/no)
- Formal test plans and procedures? (yes/no)
- Configuation Mgt Plan or equivalent? (yes/no)
- Quality Plan? (yes/no)
- Formal ILS Plans or equivalent? (yes/no)
- Requirements Documents and Specifications
  -- Functional Requirements Document (FRD) or equivalent? (yes/no)
  -- System Specification Document (SSD) or equivalent? (yes/no)
  -- Software Requirements Document (SRD) or equivalent? (yes/no)
  -- Software Design Document (SDD) or equivalent? (yes/no)
  -- Subsystem specifications? (yes/no)
  -- Software unit folders? (yes/no)
  -- ________
  -- ________
  -- ________
  -- ________
  -- ________

**DESIGN HERITAGE, DESIGN/TECHNOLOGY DIFFICULTY MEASURE**

Evaluation categories: Off the Shelf, Minor Modification, Redesign, Major Redesign, Original Design, Required Technology Breakthrough

- Overall design heritage: The Model 60 is a derivative of the Model 55 which was introduced in 1981. The Model 55 underwent several performance upgrades (1983 and 1984), and then the Model 55B was introduced in 1985. Later, the Model 55C was introduced which incorporated the earlier aerodynamic and performance improvements. The Model 60 retains the improvements made to the Model 55, but adds new elements to the same basic airframe. Redesign.
- Airframe
  -- Wings, flaps, spoilers, ailerons (Design, Mfr, Support): Based on Model 55. Improved aerodynamics. Redesign.
  -- Fuselage and nose cone/radome (Design, Mfr, Support):

Fuselage is a 3.5 ft stretched version of the Model 55 fuselage. Redesign.

-- Tail, rudder, horizontal stabilizers, elevators (Design, Mfr, Support): Essentially the same as the Model 55. Some minor aerodynamic changes. Minor modification.

-- Doors (Design, Mfr, Support): Essentially the same as the Model 55. Off-the-shelf.

-- Landing Gears, tires, and brakes (Design, Mfr, Support): Essentially the same as the Model 55. Off-the-shelf.

-- Fuel Tanks (Design, Mfr, Support):

-- Antennas (Design, Mfr, Support):

-- Canopy/Windows (Design. Mfr, Support): Essentially the same as the Model 55. Off-the-shelf.

- Propulsion
  -- Propulsion Unit (Design, Mfr, Support): Pratt & Whitney Canada PW305A turbofan engines. (I don't know if it was developed for the Model 60 or it already existed). Engines had been flown before on the P&W Canada Boeing 720 testbed aircraft.

  -- Attachment (Design, Mfr, Support):

  -- Engine Reversers (Design, Mfr, Support): Rohr engine reversers. (I don't know anything of their heritage).
- APU (Design, Mfr, Support): None
- Avionics (hardware and software)
  -- Cockpit displays (Design, Mfr, Support): Collins Pro Line 4 avionics system, IDS-850 Integrated Display System. (I don't know if it is the same as the Model 55, is off-the-shelf, or was developed specifically for the Model 60.

  -- Navigation/Guidance units (Design, Mfr, Support): Collins Syst IV

  -- Communications (Design, Mfr, Support): Collins

  -- Radars (Design, Mfr, Support): Standard Collins WXR-840 weather radar. Off-the-shelf.

  -- Flight safety/collision avoidance (Design, Mfr, Support):

  -- Automatic landing system (Design, Mfr, Support): N.A

  -- Flight Computers and autopilot (Design, Mfr, Support): Equipped with a single Collins FMS-850 flight management system computer. (I don't know if it is the same as the Model 55).

  -- Entertainment System (Design, Mfr, Support):

  -- IFF (Design, Mfr, Support): N/A

-- Fire Control (Design, Mfr, Support): N/A
-- Targeting System (Design, Mfr, Support): N/A
-- Penetration Aids (Design, Mfr, Support): N/A
-- Radar warning receiver (Design, Mfr, Support): N/A
-- Avionics Integration (Design, Implementation): ____________

-- Others? ____________

- Flight Controls (Design, Mfr, Support): Same as 55
- Fuel system (Design, Mfr, Support): Same as 55 except fuselage tank enlarged
- Passenger escape system (Design, Mfr, Support): N/A
- Environmental control system (heat & A/C) (Design, Mfr, Support): Essentially the same as the Model 55. Off-the-shelf.
- Oxygen system (Design, Mfr, Support): Essentially the same as the Model 55. Off-the-shelf.
- Ejection Seat (Design, Mfr, Support): N/A
- BITE/Central Integrated Checkout (Design, Mfr, Support): ____________

-- Level of BITE on aircraft (High, Medium, Low)
- Cargo Loading/Unloading System (Design, Mfr, Support): N/A
- Aerial Refueling System (Design, Mfr, Support): N/A
- Weapons Delivery Equipment (Design, Mfr, Support): N/A
- Support Elements
  -- New ground support equipment/test equipment? (Design, Mfr, Support): Same as 55 except for engine

  -- New maintenance procedures (Computer based?): Same as 55

  -- New training equipment/simulators (Design, Mfr, Support): Same except engine

  -- New training procedures? (yes/no) Computer based? (yes/no)
  -- New ground facilities (Design, Mfr, Support): NA.

- Integration (Design, Implementation): NA.

- Overall composite content % by weight: Less than 5%
- Total number of parts on aircraft
  -- Not including rivets and fasteners: ?
  -- Including rivets and fasteners: ?
- Design remained stable after start of production? (Production configuration consistency) Yes -
  -- How stable? (High, Medium, Low)
  -- Are there major difference between the earlier and later production deliverables due to quality - rework and repair - issues?) No - only new options, minor improvements in cabin etc.

-- Due to redesigns to correct performance requirements shortfalls? NONE

**MISSION DIFFICULTY MEASURE (Requirements or actuals)**

- Range (unrefueled): ~~2,800~~ 2740 NM
- Payload (lbs) (passengers, cargo, weapons):
- Fuel Capacity: ~~7910~~ lbs 7910 POUNDS
- Std empty weight: 13,750 lbs
- Maximum takeoff weight: 22,750 lbs OPTIONAL 23,100 BEING RAISED TO 23500
- Payload fraction (payload/max t/o wt): 7% ; 40% INCLUDING FUEL
- Top speed: 464 KNOTS
- Cruise speed: Mach .81
- Mission reliability/availability: 99%
- Maneuverability (deg roll/sec):
- Runway (unpaved landing/takeoff): No
- Cargo airdrop: No
- Aerial refueling: No
- Reduced radar cross section: No
- Weapon delivery: No

**REQUIREMENTS COMPLIANCE MEASURE**

- Areas of major non-compliance/reqmts reductions: (For example, did the Model 60 meet range, engine efficiency, and weight requirements/goals?)

**DEVELOPMENT ENVIRONMENT MEASURE**

- Extent of customer/market involvment in defining requirement for the new aircraft? MAJOR INPUT WAS FROM SALES DEPARTMENT
- Requirements remained stable throughout development? (yes/no)
  -- List major changes?
- Funding stability? (High, Medium, Low)
- Company full-funding, company risk sharing funding with partners, or government funding? COMPANY FULL FUNDING
- Business risk - was development program started before or after firm orders for the breakeven quantity were received? BEFORE
- Organizational structure and personnel stability? (High, Medium, Low)

- Stability of subcontractor/vendor team? (High, Medium, Low)
- Company background in developing the aircraft: Learjet has been designing and building business jets for over 30 years. The Model 60 is a derivative of the Model 55.
- Government oversight of development? (High, Medium, Low, none)
- Government oversight of flight testing/certification? (High, Medium, Low, none)
- Level of customer/user interface with developers (High, Medium, Low)
- Level of security measures (High, Medium, Low)
- Initial tooling established for limited or long term production? BASED ON 150 UNITS